DARK MATTER: MOTIVATION, CANDIDATES AND SEARCHES

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Abstract
The physical nature of most of the gravitating mass in the universe is completely mysterious. The astrophysical evidence for the presence of this dark matter and astrophysical constraints on its properties will be reviewed. The most popular dark-matter candidates will be introduced, and current and future attempts to search for them directly and indirectly will be discussed.

1 INTRODUCTION

The question of what makes up the mass density of the universe is practically as old as extragalactic astronomy which began with the recognition that nebulae such as M31 in Andromeda are actually galaxies like our own. Some of them appear in gravitationally bound clusters. From the Doppler shifts of the spectral lines of the galaxies in the Coma cluster, Zwicky derived in 1933 their velocity dispersion and could thus estimate the cluster mass with the help of the virial theorem [1]. He concluded that the Coma cluster contained far more dark than luminous matter when he translated the luminosity of the galaxies into a corresponding mass. Since then evidence has mounted that on galactic scales and above the mass density associated with luminous matter (stars, hydrogen clouds, x-ray gas in clusters, etc.) cannot account for the observed dynamics on those scales [2, 3, 4, 5]. In the mid 1970s it had become clear that dark matter was an unavoidable reality [6] and by the mid 1980s the view had become canonical that the universe is dominated by an unknown form of matter or by an unfamiliar class of dark astrophysical

Fig. 1: DENNIS THE MENACE $^{(R)}$ used by permission of Hank Ketcham and (c) by North America Syndicate.

objects [7]. Besides the origin of cosmic rays and γ-ray bursts (two major unsolved puzzles) the physical nature of dark matter is no doubt the most stunning astrophysical mystery.

A popular hypothesis for the solution of this problem originated in a seminal paper by Cowsik and McClelland in 1973 where they speculated that the dark matter of galaxy clusters could consist of neutrinos if these weakly interacting particles had a mass of a few eV [8]. About ten years earlier the cosmic microwave background (CMB) radiation had been detected and had almost overnight propelled the big-bang cosmogony from an obscure hypothesis to the standard theory of the early universe. If the world originated from a hot phase of thermal equilibrium, then all possible particles or forms of radiation must have been produced in amounts which are easily calculable relative to the density of microwave photons, leading to the prediction of a "cosmic neutrino sea" in analogy to the CMB. This had allowed Gershtein and Zeldovich in 1966 to derive a stringent limit on the ν_μ mass [10, 11], a second neutrino flavor which had been discovered in 1962.

A well-known phase-space constraint on how many massive neutrinos can be packed into a galaxy leads to a lower limit of about $20-30\,\mathrm{eV}$ if they are supposed to be the dark matter in these systems [9]. This "Tremaine-Gunn limit" is barely compatible with the *upper* limit of about $40\,\mathrm{eV}$ from the overall cosmic mass density. Therefore, neutrinos certainly cannot be the dark matter on the smallest scales where its existence is established, most notably in dwarf galaxies. In addition, modern theories of the formation of galaxies and larger cosmic structures reveal that particles which stay relativistic for a long time in the expanding universe ("hot dark matter") prevent the formation of small-scale structure. Thus, even if there were enough phase space for $40\,\mathrm{eV}$ neutrinos to be the galactic dark matter, one could not explain how these collisionless particles would have been able to cluster on these scales.

The alternative is "cold dark matter," particles which became nonrelativistic early. While this hypothesis works well from the structure-formation perspective, it implies the existence of completely new particles or else primordial black holes. Assuming the existence of stable weakly interacting massive particles (WIMPs) one can predict their cosmic abundance from their mass and annihilation cross section alone. If their interaction strength is roughly given by Fermi's constant, then they would need a mass in the $10\,\mathrm{GeV}$ range to be the dark matter of the universe. While in the 1980s one often discussed generic WIMPs as dark-matter candidates, the attention today has focussed almost entirely on supersymmetric extensions of the standard model which predict the existence of the requisite particle in the form of a "neutralino." The only other cold dark matter candidate which is seriously discussed today are axions which are very weakly interacting pseudoscalar bosons.

Meanwhile it is not obvious that the simplest cold dark matter cosmologies are complete. It may be that structure formation requires several different components, for example a certain fraction of neutrinos plus a dominating share of neutralinos or axions ("hot plus cold dark matter"). In addition, there may be a homogeneous mass density in the form of vacuum energy which would play the role of a cosmological constant. The nature of dark matter may be quite diverse!

The most exciting development of the 1990s is the emergence of a great variety of real experimental projects to search for all of the well-motivated candidates in our own galaxy. The microlensing search for dark stars has actually produced first candidates ("MACHOs") which are, however, difficult to interpret. Direct and indirect search experiments for WIMP and axion dark matter in the galaxy have reached a sensitivity where they begin to have a realistic chance of finding these elusive particles. In addition, the upcoming CMB satellites will be able to measure temperature fluctuations on very small angular scales, allowing for a precision determination of various cosmological parameters, notably the exact abundance of baryonic and nonbaryonic matter. One would expect these measurements to remove any lingering doubt about the reality of nonbaryonic dark matter.

In these lectures I will review the astrophysical motivation for dark matter and discuss the arguments which reveal that it is probably not purely baryonic, and not purely in the form of massive neutrinos. I will then proceed to discuss various candidates (dark stars, neutrinos, WIMPs, axions) and the current attempts to search for them by astronomical, neutrino-astronomical, and laboratory methods.

Fig. 2: M31, the Andromeda galaxy, the closest spiral galaxy to the Milky Way at a distance of about $750\,\mathrm{kpc}$.

2 DYNAMICAL EVIDENCE

2.1 Rotation Curves of Spiral Galaxies

Why are astronomers so sure that there are large amounts of dark matter lurking everywhere in the universe? The flat rotation curves of spiral galaxies provide perhaps the most direct and surely the most impressive evidence. These systems consist of a central bulge and a very thin disk which is stabilized against collapse by angular momentum conservation. It is then natural to use the Doppler shift of spectral lines to obtain a rotation curve, i.e. the orbital velocity of the disk as a function of radius. For the Andromeda galaxy (Fig. 2), our next-door neighbor at a distance of about[1] $750\,\mathrm{kpc}$, the rotation curve was first measured by Babcock in 1938 [12]. Later when it became possible to measure galactic rotation curves far out into the disk a most unusual behavior emerged. The orbital velocity rose roughly linearly from the center outward until it reached a typical value of around $200\,\mathrm{km\,s^{-1}}$. The rotation curve then stayed flat at this velocity out to the largest measured radii, a systematic trend clearly diagnosed as such by Freeman in 1970 [13]. This behavior is completely unexpected because the surface luminosity of the disk falls off exponentially with radius [13]

$$I(r) = I_0\, e^{-r/r_\mathrm{D}}, \tag{1}$$

where r_D is the "disk scale-length." Therefore, one would expect that most of the galactic mass is concentrated within a few scale-lengths and that the orbital velocity v_rot of the disk material is determined by this mass just as the orbital velocity of the planets in the solar system is dominated by the mass of the Sun. Because in such a system we have $v_\mathrm{rot} = \sqrt{G_\mathrm{N} M/r}$ (central mass M, Newton's constant G_N) one expects the Keplerian $v_\mathrm{rot} \propto r^{-1/2}$ behavior in analogy to the solar system (Fig. 3).

[1] Astronomical distances are usually measured in parsec (pc) where $1\,\mathrm{pc} = 3.26$ light-years $= 3.08 \times 10^{18}\,\mathrm{cm}$. As a matter of general orientation note that $1\,\mathrm{pc}$ is a typical distance between stars within the galactic disk, $10\,\mathrm{kpc}$ is a typical scale for a galactic disk (the Sun is at $8.5\,\mathrm{kpc}$ from the center of the Milky Way) galaxies are typically $1\,\mathrm{Mpc}$ away from each other, and the visible universe has a radius of about $3\,\mathrm{Gpc}$.

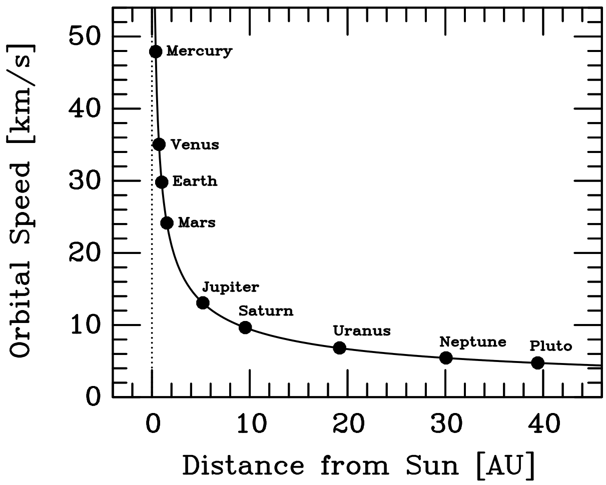

Fig. 3: Rotation curve of the solar system which falls off as $1/\sqrt{r}$ in accordance with Kepler's law. The astronomical unit (AU) is the Earth-Sun distance of $1.50 \times 10^{13}\,\mathrm{cm}$.

The non-Keplerian, essentially flat nature of the rotation curves is supported by systematic optical studies of many spiral galaxies [14, 15]. The most convincing evidence for this unexpected behavior, however, arises from radio observations. Spiral galaxies typically have neutral hydrogen in their disks which can be observed by its 21 cm line emission. The hydrogen can be observed to much larger galactic radii than optical tracers (Fig. 4) so that one can obtain far more extended rotation curves [16, 17, 18] than by purely optical observations which typically stop at $1.5{-}3.5$ disk scale-lengths. A case in point is the galaxy NGC 6503 where $r_{\rm D} = 1.73\,\mathrm{kpc}$ while the last measured hydrogen point is at $r = 22.22\,\mathrm{kpc} = 12.8\,r_{\rm D}$. The measured rotation curve is shown in Fig. 5 together with the relative components ascribed to the gravity of the disk alone and gas alone.

The difference to the rotation curve which is expected from the luminous material is ascribed to the gravitational effect of dark matter. A number of strong arguments suggest that this material cannot be part of the galactic disk itself. First, the distribution of stars vertically to the galactic disk in our galaxy together with their vertical velocity dispersion reveals that there cannot be any significant amount of dark matter confined to the disk, although it has been the subject of some debate since 1932 if there is *some* disk dark matter [19]. Second, a thin self-gravitating disk is dynamically unstable. Third, the hydrogen of the disk tends to be vertically far more extended than would be expected if all of the gravitating matter were in the disk, especially at large galactocentric radii (”hydrogen flaring”). Fourth, there exist ”polar ring galaxies” with material orbiting perpendicularly to the normal disk which appears to trace out a more or less spherical gravitational potential. (For a review of such arguments see [2].) An overall picture of spiral galaxies emerges where the bulge and disk are dynamically subdominant components immersed in a huge spherical ”halo” or ”corona” of dark matter. It is not crucial that this halo be strictly spherical; the overall picture does not change if the halo exhibits a significant degree of oblateness or even triaxiality.

The study of more than a thousand galactic rotation curves reveals that empirically they can be represented extremely well by a ”universal rotation curve” (URC) [20]

$$v_{\rm URC}(r) = v(r_{\rm opt}) \left\{ \left(0.72 + 0.44\,\log_{10}\frac{L}{L_*}\right) \frac{1.97\,x^{1.22}}{(x^2+0.78^2)^{1.43}} + \left(0.28 - 0.44\,\log_{10}\frac{L}{L_*}\right) \left[1 + 2.25\left(\frac{L}{L_*}\right)^{0.4}\right] \frac{x^2}{x^2 + 2.25\,(L/L_*)^{0.4}} \right\}^{1/2} , \quad (2)$$

where $x \equiv r/r_{\rm opt}$, L is the luminosity of the galaxy, and the reference luminosity is $L_* \equiv 2.5 \times 10^{10} L_\odot$ in the optical B-band (blue filter) with $L_\odot$ the solar luminosity. The optical radius $r_{\rm opt}$ is defined to

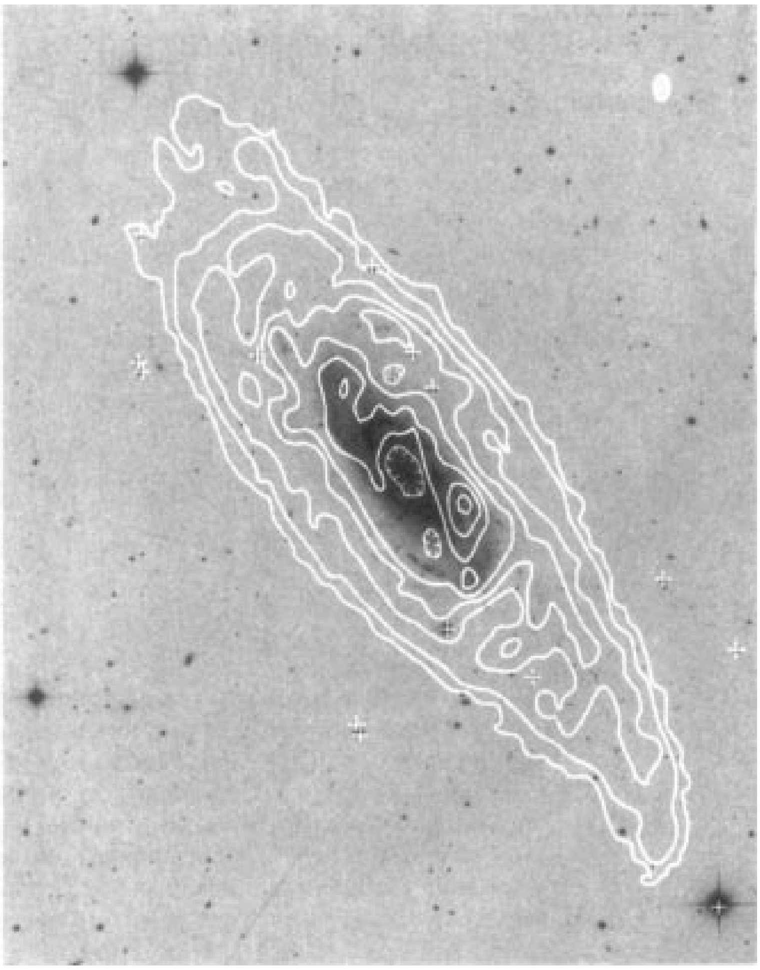

Fig. 4: Image of the spiral galaxy NGC 3198 with a superimposed contour map of the column density of hydrogen gas [17].

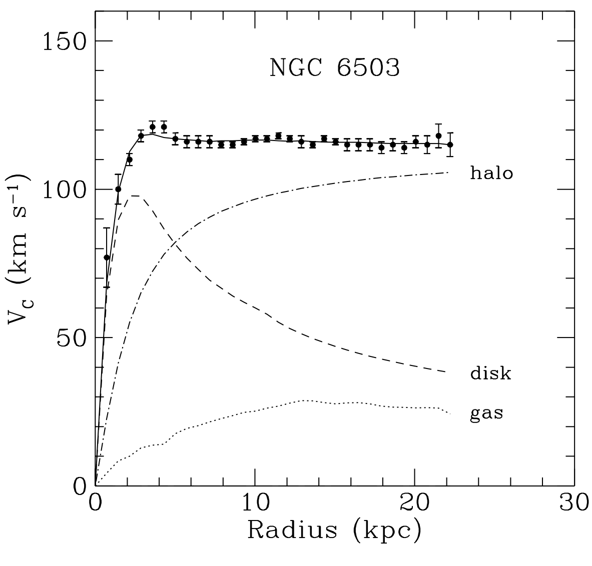

Fig. 5: Rotation curve of the spiral galaxy NGC 6503 as established from radio observations of hydrogen gas in the disk [18]. The last measured point is at 12.8 disk scale-lengths. The dashed line shows the rotation curve expected from the disk material alone, the dot-dashed line from the dark matter halo alone.

encompass 83% of the integrated light; for the exponential disk of Eq. (1) we have $r_{\rm opt} = 3.2\,r_{\rm D}$. Empirically, then, galactic rotation curves depend on only two parameters, the total luminosity and the optical radius.

Galaxies presumably form by the infall of material in an overdense part of the universe which has decoupled from the overall cosmic expansion. The dark matter is supposed to undergo "violent relaxation" and form a "virialized system." This picture has led to a simple model of dark-matter halos as "modified isothermal spheres." The radial density profile is taken to be

$$\rho(r) = \frac{v_\infty^2}{4\pi G_{\rm N} r_{\rm c}^2}\,\frac{r_{\rm c}^2}{r_{\rm c}^2 + r^2}, \tag{3}$$

where $r_{\rm c}$ is a core radius and v_∞ the plateau value of the flat rotation curve. This sort of model is consistent with the universal rotation curve of Eq. (2) if one disentangles the luminous-matter contribution from the total rotation curve. At large radii such a distribution leads to a strictly flat rotation curve.

The URC reveals that the more luminous galaxies are dominated by luminous matter to relatively large radii while the fainter ones are more dominated by dark matter. The faintest (smallest) galaxies are dominated by dark matter even in their central regions. Therefore, these systems are better laboratories than bright spirals to test theories of galaxy formation. Actually, the best measured rotation curve is that of the dwarf spiral DDO 154 which extends out to about 20 disk scale lengths. In such systems the

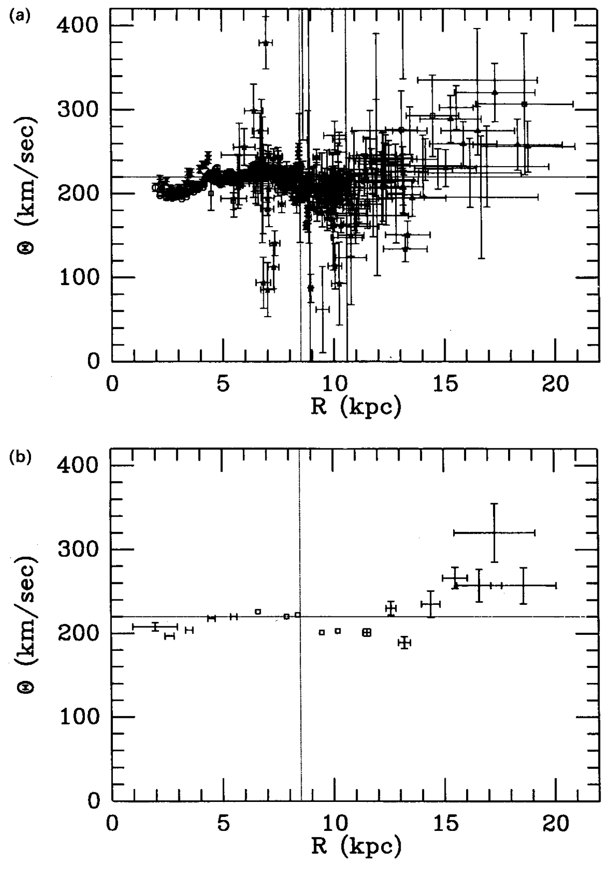

Fig. 6: Rotation curve of the Milky Way where Θ stands for $v_{\rm rot}$ [25]. The dotted lines represent the 1985 International Astronomical Union values of $v_{\rm rot} = 220\,{\rm km\,s^{-1}}$ at the location of the solar system which is taken to be at a galactocentric radius of $8.5\,{\rm kpc}$. The upper panel represents all data as quoted in Ref. [25], the lower panel their smoothed data set.

rotation curve falls off at large radii; their dark matter density profile is well represented by [21]

$$\rho(r) = \rho_0 \, \frac{r_0^3}{(r + r_0)(r^2 + r_0^2)}, \tag{4}$$

where ρ_0 is the central density and r_0 a core radius. The integral mass diverges only logarithmically with radius. The large-r behavior of this model is predicted by recent high-resolution N-body simulations of galaxy formation in a cold dark matter cosmology [22]. Towards the galactic center, however, these simulations predict a density cusp of the form $[r\,(r^2 + r_0^2)]^{-1}$, in apparent contradiction with the observations. This discrepancy is a possible problem for cold dark matter cosmologies [23] even though the reality of the discrepancy has recently been questioned [24].

For the purpose of the direct detection of dark matter our own Milky Way is the most interesting system. Its rotation curve is far more difficult to obtain than that of an external galaxy because we can see only part of it (most is obscured by dust in the disk) and it is difficult to obtain reliable galactocentric distances for the tracers. Still, the rotation curve of Fig. 6 shows that the Milky Way conforms to the usual picture. The approximate plateau value for the rotation velocity is $220\,\mathrm{km\,s^{-1}}$. For dark matter search experiments the most critical quantity is the dark matter density in the solar neighborhood. The canonical value usually adopted for the interpretation of the experiments is

$$\rho_{\mathrm{DM}} = 300\,\mathrm{MeV\,cm^{-3}}. \tag{5}$$

It must be kept in mind, however, that this number depends on the model adopted for the galactic dark-matter halo and thus is uncertain to within, perhaps, a factor of two [26].

2.2 Cosmic Density Contribution of Galaxies

Another important question is how much the total masses of galaxies contribute to the overall density of the universe. It is usually expressed in terms of the cosmic critical density [5]

$$\rho_{\mathrm{crit}} \equiv \frac{3H_0^2}{8\pi G_{\mathrm{N}}} = h^2\, 1.88 \times 10^{-29}\,\mathrm{g\,cm^{-3}}, \tag{6}$$

where H_0 is the present-day Hubble expansion parameter. It is usually written as

$$H_0 = h\,100\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{7}$$

in terms of the dimensionless parameter h which appears in various powers in most quantities of cosmological interest. Observationally it lies in the range $0.4 \lesssim h \lesssim 1.0$ with

$$0.5 \lesssim h \lesssim 0.8 \tag{8}$$

the currently most favored interval [27]. The average contribution ρ of various matter components to the cosmic density is usually expressed by the parameter

$$\Omega \equiv \rho/\rho_{\mathrm{crit}}. \tag{9}$$

In the framework of the usual Friedmann-Lemaître-Robertson-Walker cosmology [5] the spatial cosmic geometry is Euclidean for $\Omega = 1$ ("flat universe"), the spatial curvature is negative for $\Omega < 1$ ("open universe"), and it is positive for $\Omega > 1$ ("closed universe").

The contribution of galaxies to Ω is related to the luminosity density of the universe which is found to be $(1.7 \pm 0.6) \times 10^8\, h\, L_\odot \mathrm{Mpc}^{-3}$ in the V (visual) spectral band [29]. This luminosity density can be translated into a mass density by a multiplication with the mass-to-light ratio M/L of a given class of systems, often denoted by Υ (upsilon). Mass-to-light ratios are usually expressed in solar units $M_\odot/L_\odot$ so that for the Sun $\Upsilon = 1$. Therefore, the cosmic mass density is $\Omega = (6.1 \pm 2.2) \times 10^{-4}\, h^{-1}\, \Upsilon_V$. The luminosity of stars depends sensitively upon their mass and their stage of evolution. Stellar populations for which the mass and luminosity can be determined independently include globular clusters and the disks of spiral galaxies which have an Υ of a few. The stars in the solar neighborhood have $\Upsilon \approx 5$. Taking this as a representative value we find for the luminous mass density of the universe $\Omega_{\rm lum} h \approx 0.003$. Several methods give values which are consistent with the range [30]

$$0.002 \lesssim \Omega_{\rm lum} h \lesssim 0.006. \tag{10}$$

Therefore, the luminous matter alone is far from the cosmic critical density.

The mass-to-light ratios of galactic haloes are typically at least around $30\,h$ as far as the measured rotation curves reach, giving a cosmic mass density of at least

$$\Omega_{\rm gal} \gtrsim 0.03{-}0.05. \tag{11}$$

The flat rotation curves indicate that their integral mass increases as $M(r) \propto r$. Because the rotation curves tend to stay flat out to the largest radii where tracers are available, the true size of galactic dark matter halos and thus the total cosmic mass in galaxies is not well known. Estimating the extent of dark-matter haloes from satellite dynamics yields $\Omega_{\rm gal} h = 0.2{-}0.5$ [31].

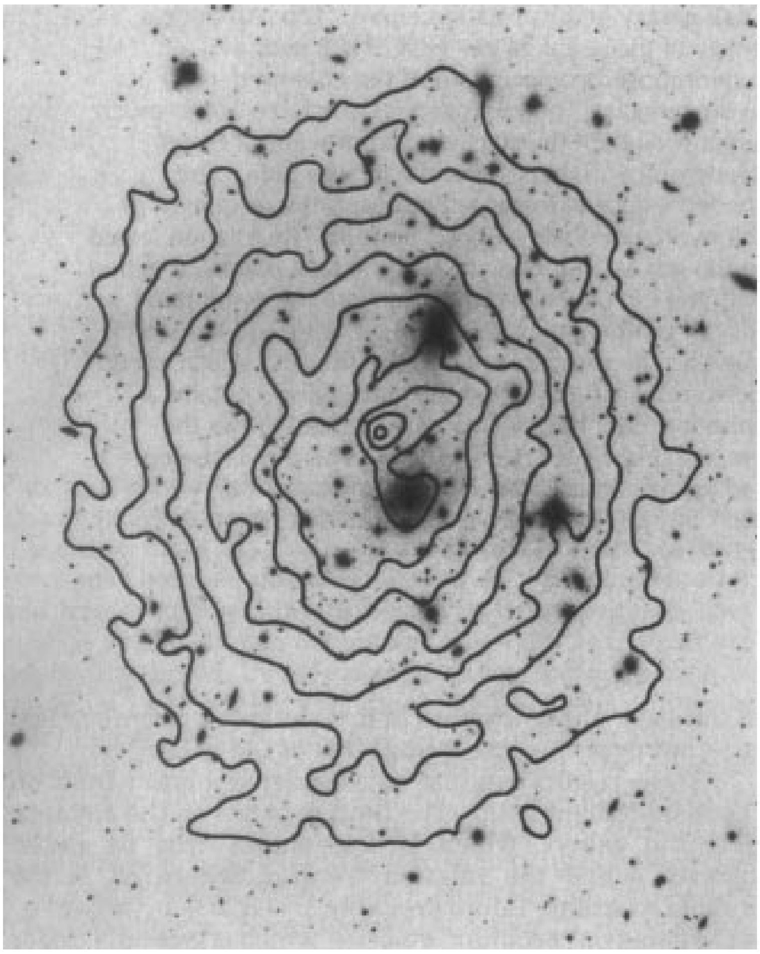

Fig. 7: Coma cluster of galaxies. Contour map of the x-ray surface brightness measured by the Einstein satellite superimposed on an optical image. (Picture by William Forman and Christine Jones, Harvard-Smithonian Center for Astrophysics, here reproduced from Ref. [3].)

2.3 Clusters of Galaxies

Clusters of galaxies are the largest gravitationally bound systems in the universe. We know today several thousand clusters; they have typical radii of $1.5\,\mathrm{Mpc}$ and typical masses of $5 \times 10^{14}\,M_\odot$. Zwicky first noted in 1933 that these systems appear to contain large amounts of dark matter [1]. He used the virial theorem which tells us that in a gravitationally bound system in equilibrium

$$2\langle E_{\mathrm{kin}}\rangle = -\langle E_{\mathrm{grav}}\rangle \tag{12}$$

where $\langle E_{\mathrm{kin}}\rangle = \frac{1}{2}m\langle v^2\rangle$ is the average kinetic energy of one of the bound objects of mass m and $\langle E_{\mathrm{grav}}\rangle = -mG_{\mathrm{N}}\langle M/r\rangle$ is the average gravitational potential energy caused by the other bodies. Measuring $\langle v^2\rangle$ from the Doppler shifts of the spectral lines and estimating the geometrical extent of the system gives one directly an estimate of its total mass M. As Zwicky stressed, this "virial mass" of the clusters far exceeds their luminous matter content, typically leading to a mass-to-light ratio of around 300. From current estimates for virial cluster masses one finds for the cosmic matter density [32]

$$\Omega_{\mathrm{M}} = 0.24 \pm 0.05 \pm 0.09, \tag{13}$$

where the first uncertainty is a statistical 1σ error while the second is an estimate of systematic uncertainties. It was assumed that the average cluster M/L is representative for the entire universe which is not to be taken for granted as most galaxies are actually not in clusters but in the general field.

After the mid 1960s when x-ray telescopes became available it turned out that galaxy clusters are the most powerful x-ray sources in the sky [33]. The emission is extended over the entire cluster (Fig. 7) and thus reveals the presence of large amounts of "x-ray gas," a hot plasma ($T = 10^7$–10^8 K) where x-rays are produced by electron bremsstrahlung. Assuming this gas to be in hydrostatic equilibrium one may again apply essentially the virial theorem (with the gas particles being the test bodies) to estimate the total cluster mass, generally giving approximate agreement (within a factor of 2) with the virial mass estimates. The total mass in the x-ray gas is typically in the 10–20% range [34], i.e. clusters contain more baryonic matter in the form of hot gas than in the form of stars in galaxies. This large baryon fraction relative to the total cluster mass, if taken to be representative of the entire universe, indicates that the amount of nonbaryonic dark matter exceeds the cosmic baryon content only by a factor of around 10, a finding with important cosmological ramifications [35] as we shall see below.

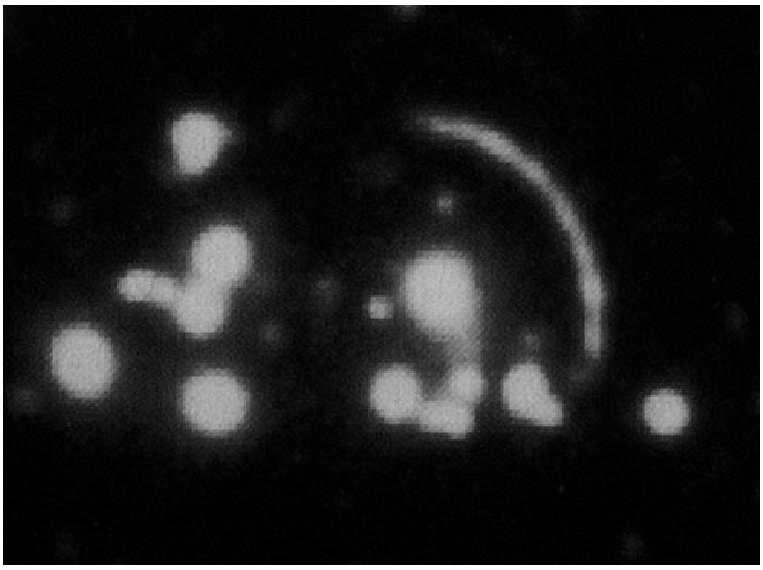

Fig. 8: Giant arc in the cluster Cl 2244-02 which is at a redshift of $z = 0.33$ while the source which is imaged as an arc is at $z = 2.24$.

Fig. 9: Hubble Space Telescope (HST) image of the cluster Abell 2218, showing a number of arcs and arclets around the two centers of the cluster (NASA HST Archive).

In the mid 1980s one began to observe huge arc-like features in galaxy clusters [36, 37] with one prominent example shown in Fig. 8. The cluster galaxies and these ”giant arcs” are at very different cosmological redshifts and thus at very different distances. The standard interpretation is that the arc is the image of a distant background galaxy which is almost lined up with the cluster so that it appears distorted and magnified by the gravitational lens effect [38]. A source and a gravitational deflector which are precisely lined up would give rise to a ring-like image (”Einstein ring”); the giant arcs are essentially partial Einstein rings. The cluster mass estimates derived from this interpretation, again, reveal large amounts of dark matter in rough agreement (approximate factor of 2) with the virial mass estimates, even though the lensing masses tend to be systematically larger [39].

While the appearance of giant arcs requires a special alignment between source and lens, the image of every background galaxy in the vicinity of a given cluster will be distorted, causing the appearance

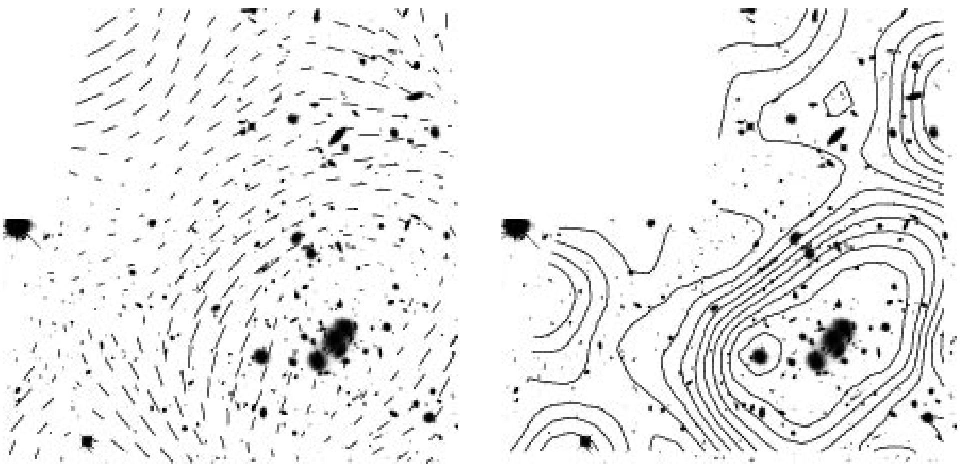

Fig. 10: HST image of the cluster Cl 0024, overlaid on the left with the shear field obtained from an observation of arclets with the Canada-France Hawaii Telescope (Y. Mellier and B. Fort), and on the right with the reconstructed surface-mass density determined from the shear field (C. Seitz et al.). (Figure from Ref. [39].)

of innumerable "arclets" (Fig. 9). This "weak lensing effect" allows for a systematic study of cluster mass distributions [40]. One uses the statistical distributions of arclets to reconstruct the shear field of gravitational image distortions and from there one can derive cluster mass distributions (Fig. 10). This approach to mapping out cluster dark matter has turned into a new topical field of astronomical research in its own right [37, 39, 40, 41].

2.4 Large-Scale Motion

On scales larger than clusters the motion of galaxies is dominated by the overall cosmic expansion. Still, they exhibit "peculiar velocities" relative to the overall cosmic flow. For example, our own group of galaxies moves with a speed of $627 \pm 22\,\mathrm{km\,s^{-1}}$ relative to the reference frame defined by the cosmic microwave background radiation. For external galaxies the determination of peculiar velocities requires

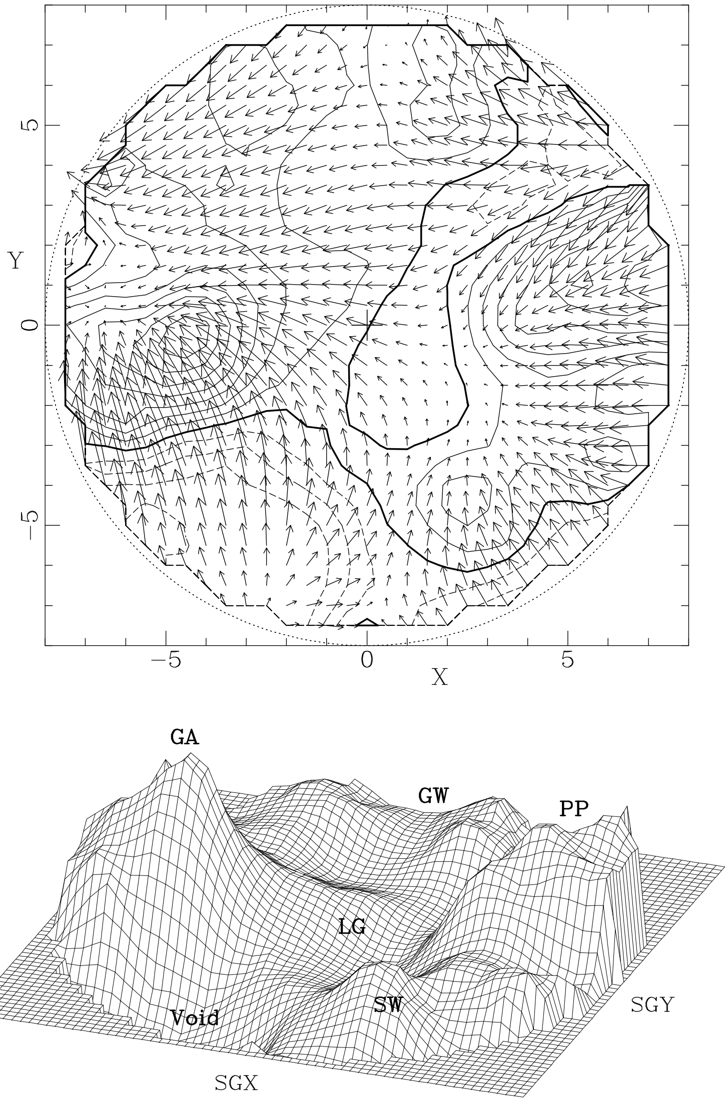

Fig. 11: The fluctuation fields of velocity and mass-density in the Supergalactic Plane as recovered by the POTENT method from the Mark III velocities [42] of about 3000 galaxies with $12\,h^{-1}\,\mathrm{Mpc}$ smoothing [43]. The vectors are projections of the 3-D velocity field in the frame of the cosmic microwave background. Dashed contours mark underdensities, solid ones overdensities. Distances are in the space of Hubble recession velocities in units of $1000\,\mathrm{km\,s^{-1}}$ which corresponds to $h^{-1}\,10\,\mathrm{Mpc}$, i.e. the reconstruction goes out to a distance of $h^{-1}\,80\,\mathrm{Mpc}$. The marked structures are the local group (LG), the "great attractor" (GA), the Coma "great wall" (GW), the Perseus-Pisces (PP) region, and the "southern wall" (SW).

the determination of their redshifts and an independent measure of distance. A homogeneous catalog of about 3000 galaxies (Mark III catalog [42]) has recently been completed for this purpose.

In the context of the standard gravitational instability theory of structure formation the peculiar motions are attributed to the action of gravity over the age of the universe, caused by the matter density inhomogeneities which give rise to the formation of structure. The observed large-scale velocity fields together with the observed galaxy distributions can then be translated into a measure for the mass-to-light ratio which is necessary to explain the large-scale flows. An example for the reconstruction of the matter density field in our cosmological neighborhood from the observed velocity field by means of the POTENT method is shown in Fig. 11. The cosmic matter density inferred by such methods is [43]

$$\Omega_{\rm M} > 0.3, \tag{14}$$

which is claimed to be a 95% C.L. lower bound. Related methods which are more model-dependent give even larger estimates.

2.5 Cosmic Age

The dynamical density measured on galactic scales up to those of large-scale flows provide a lower limit to the average cosmic matter density $\Omega_{\rm M}$. Naturally, the true $\Omega_{\rm M}$ could be larger than indicated by Eq. (14). Less reliable arguments concerning the dynamics of the large-scale structure and large-scale flows already point to values for $\Omega_{\rm M}$ not much below the critical value 1 [43]. The cosmic matter density determines the dynamical evolution of the universe through the Friedmann equation. Therefore, a critical measure of $\Omega_{\rm M}$ is provided by the cosmic age t_0 as infered from the ages of the oldest stars in conjunction with measurements of the present-day expansion rate H_0.

The known or conjectured forms of radiation (cosmic microwave photons and other electromagnetic background radiations, massless neutrinos, gravitational waves) are thought to contribute only $\Omega_{\rm rad}h^2 \approx 3\times 10^{-5}$ which shall be ignored in the present discussion. If we thus assume for the moment that the total cosmic energy density $\Omega_{\rm tot}$ is essentially identical with the matter density $\Omega_{\rm M}$, and if we assume in addition that $\Omega_{\rm M} \leq 1$, the relationship between age and matter content is [5] (Fig. 12)

$$H_0 t_0 = \frac{\Omega_{\rm M}}{2(1-\Omega_{\rm M})^{3/2}}\left[\frac{2}{\Omega_{\rm M}}\,(1-\Omega_{\rm M})^{1/2} - {\rm Acosh}\left(\frac{2}{\Omega_{\rm M}}-1\right)\right]\,. \tag{15}$$

For $\Omega_{\rm M} = 1$ one finds the well-known limit $H_0 t_0 = 2/3$.

For a long time there was an ”age crisis” for the universe in that the oldest stars seemed older than its expansion age. However, recent modifications of the stellar input physics (equation of state, opacities, etc.) and particularly the new Hipparcos calibration of stellar distances have led to a revision of the age estimates for the oldest globular clusters to $10{-}13\,{\rm Gyr}$ [45]. Moreover, estimates for the Hubble constant have come down to about $0.5 \lesssim h \lesssim 0.8$ [27], leading to an allowed range of $0.5 \lesssim H_0 t_0 \lesssim 0.8$ which includes the critical-universe value $2/3$ without any problems.

The critical value $\Omega_{\rm tot} = 1$ for the total cosmic mass and energy density, corresponding to an overall Euclidean (flat) spatial geometry, is strongly favored to avoid a fine-tuning problem of cosmic inital conditions. In an expanding universe $\Omega_{\rm tot}$ evolves quickly away from 1 towards either 0 or ∞ so that the near-flatness of the present-day universe suggests $\Omega_{\rm tot} = 1$ as an exact identity. Moreover, inflationary models of the early universe generically produce a flat geometry even though one may construct fine-tuned models which can circumvent this as an absolute prediction.

However, even if the universe is flat one is not assured that $\Omega_{\rm tot}$ is dominated by matter; a cosmological constant Λ is also conceivable. This hypothesis periodically comes and goes in cosmology. In modern terms Λ arises as the vacuum energy of quantum fields and as such poses the opposite problem, i.e. why is it not much larger than the cosmologically allowed value. Its observed smallness remains

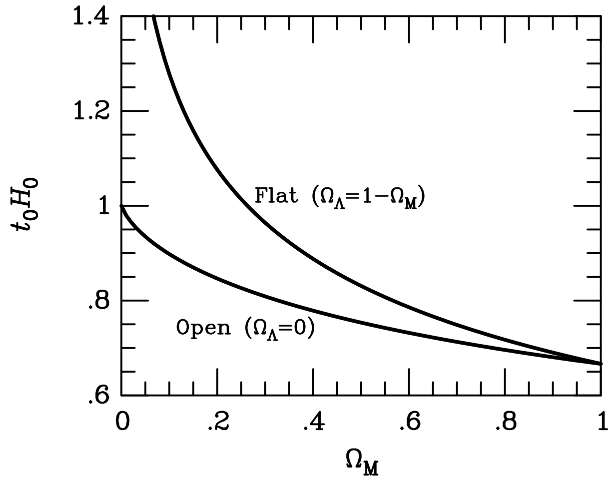

Fig. 12: Age of the universe as a function of matter content according to Eq. (15) for an open, matter dominated universe and according to Eq. (16) for a flat universe with $\Omega_\Lambda = 1 - \Omega_{\rm M}$.

unexplained and no compelling reason is known why Λ should be exactly zero [44]. Therefore, from the cosmological perspective Λ and its contribution Ω_Λ to the total energy density remains a free parameter.

A cosmological constant (vacuum energy) differs from matter in a number of important ways. Ω_Λ can be both positive or negative while $\Omega_{\rm M}$ is always positive. Vacuum energy is homogeneously distributed and thus cannot be measured dynamically on scales of galaxies, clusters, and so forth; it only affects the global dynamics of the universe. The most counter-intuitive property is that vacuum energy is not diluted by the cosmic expansion. The normal matter density $\rho_{\rm M}$ is conserved in a co-moving volume and thus is diluted as R^{-3} with the time-dependent cosmic scale-factor R while the vacuum energy density $\rho_{\rm vac}$ is constant so that its contribution grows as R^3 in a co-moving volume. Therefore, if there is any vacuum energy it dominates the dynamics at late times.

Pragmatically, then, the choice of cosmological models is between a matter-dominated open universe with no cosmological constant, a matter-dominated flat universe, and a flat universe with a certain cosmological-constant contribution ($\Omega_{\rm tot} = \Omega_{\rm M} + \Omega_\Lambda = 1$). In this latter case the age is [5]

$$H_0 t_0 = \frac{2}{3}\,\frac{1}{(1-\Omega_{\rm M})^{1/2}}\,\ln\left(\frac{1+(1-\Omega_{\rm M})^{1/2}}{\Omega_{\rm M}^{1/2}}\right), \tag{16}$$

also shown in Fig. 12. For the same $\Omega_{\rm M}$ this gives a larger expansion age than an open matter-dominated universe, and a much larger expansion age than a flat matter-dominated universe. Until recently the age crisis together with a number of arguments related to structure formation seemed to point toward a cosmological constant [46], but today this case is far less compelling even if it can still be argued [47].

3 ASTROPHYSICAL CONSTRAINTS

3.1 Big-Bang Nucleosynthesis

There are a number of strong astrophysical constraints on the possible nature of the dark matter that appears to dominate the dynamics of the universe on galactic scales and above. The first natural question is if this matter could not be just normal matter in some nonluminous form, perhaps stellar remnants such as neutron stars or black holes or molecular hydrogen clouds which are difficult to measure.

However, the overall baryonic content of the universe is strongly constrained by big-bang nucleosynthesis (BBN). When the early universe cooled below a temperature of about $1\,\rm MeV$ the β equilibrium between protons and neutrons froze out, and shortly afterward all the remaining neutrons together with the ambient protons formed $^4\mathrm{He}$ and traces of deuterium, $^3\mathrm{He}$, and $^7\mathrm{Li}$ [5]. Within the standard big-bang picture the predicted abundances depend only on one unknown comological parameter, the baryon number fraction relative to the present-day number density of cosmic microwave background photons, $\eta \equiv n_B/n_\gamma$. It is usually parametrized as $\eta_{10} \equiv \eta/10^{-10}$ and then gives

$$\Omega_{\mathrm{B}} h^2 = 3.73 \times 10^{-3}\, \eta_{10} \tag{17}$$

for the baryonic mass fraction of the universe. The standard predictions for the light-element abundances as a function of η_{10} are shown in Fig. 13.

The main problem is to get an empirical handle at the primordial light-element abundances from observations in the present-day universe. The current situation is somewhat confusing in that various measurements with their claimed uncertainties are not necessarily mutually consistent. In principle, the most sensitive "baryon meter" is the deuterium abundance. Recently, abundance measurements in intergalactic hydrogen clouds have become possible by observing deuterium and hydrogen absorption

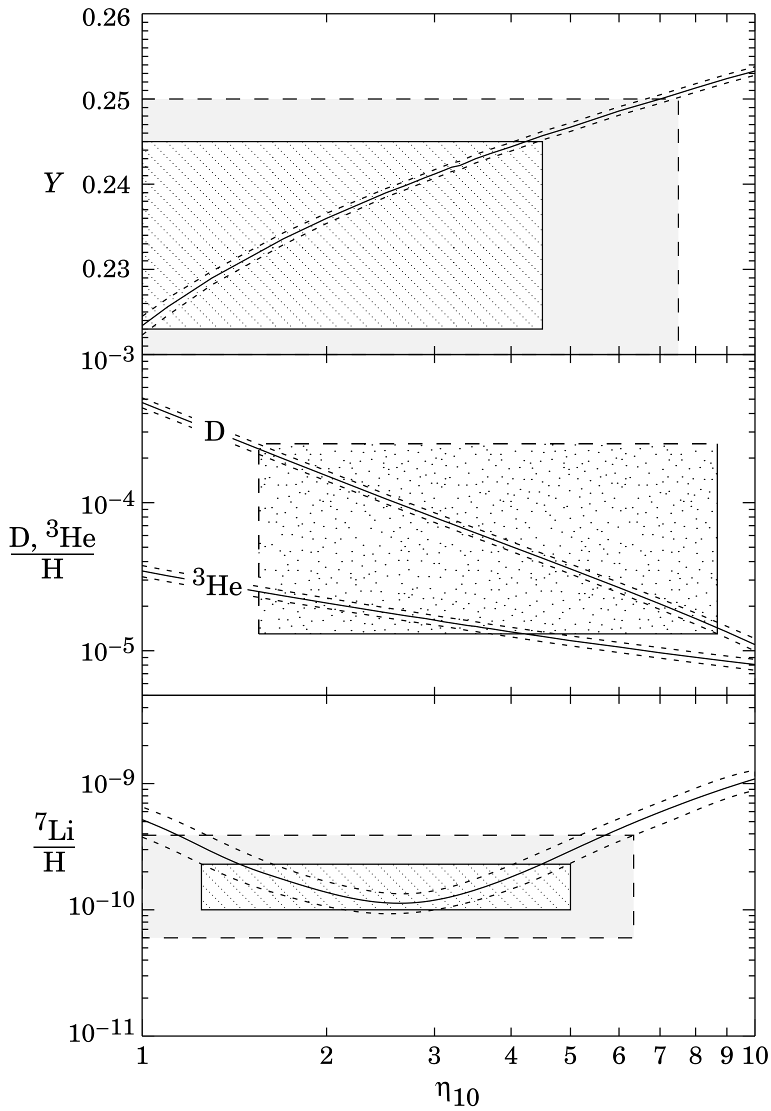

Fig. 13: Light-element abundances as a function of the baryon-to-photon ratio in the standard big-bang scenario [48]. The solid lines show the standard predictions with their errors due to nuclear cross-section uncertainties indicated by dashed lines. The boxes indicate the current observational situation where the big shaded boxes are found when the systematic uncertainties are pushed to their plausible limits.

lines from quasars as light sources. While these measurements hold a great deal of promise toward a precision determination of the primordial deuterium abundance and thus of η_{10}, the current set of results give both high [49] and low [50] values of $\mathrm{D/H} \approx 2 \times 10^{-4}$ and $(2.3 \pm 0.3) \times 10^{-5}$, respectively, which are mutually inconsistent unless the baryon distribution is vastly inhomogeneous on large scales.

In Fig. 13 the current observational situation is indicated by error boxes. Olive and Schramm [48] thus derive a currently allowed range $1.5 < \eta_{10} < 6.3$ which implies

$$0.005 < \Omega_{\mathrm{B}} h^2 < 0.024. \tag{18}$$

This allowed range for Ω_{B} is depicted in Fig. 14 as a function of the Hubble expansion parameter together with the luminous mass density of Eq. (10) and the lower dynamical mass limit Eq. (14) from the analysis of large-scale coherent flows.

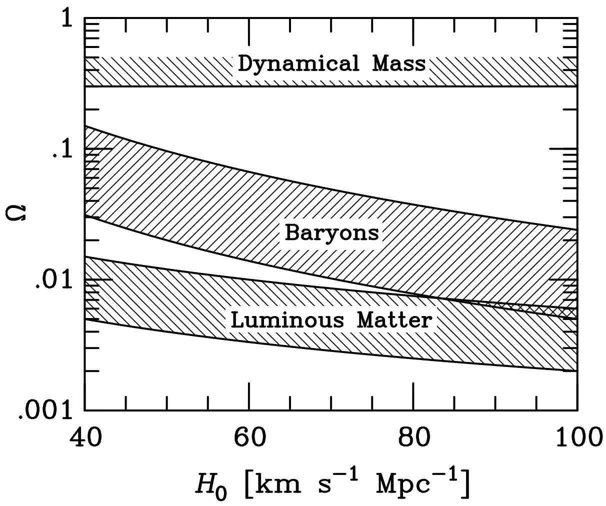

Fig. 14: Observed cosmic matter components as a function of the assumed present-day Hubble expansion parameter. The density range of luminous matter was given in Eq. (10), the lower limit to the dynamical mass density in Eq. (14), and the baryonic density inferred from BBN in Eq.(18).

The currently favored range for H_0 is between 50 and $80\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [27]. Therefore, Fig. 14 reveals that there is a gap between the cosmic baryon density and both the luminous matter density and the total matter density. Accepting this result implies that there must be a significant fraction of ”dark baryons” in the universe which never made their way into galaxies and stars, and also lots of nonbaryonic dark matter which is of a completely different physical nature.

3.2 X-Ray Clusters

We have already discussed in Sec. 2.3 that galaxy clusters contain a large fraction of baryons in the form of hot x-ray gas. Estimates of the baryon fraction in clusters relative to their total mass lead to a baryon fraction of these systems of [34, 35]

$$f_{\mathrm{B}} h^{3/2} = 0.03\text{–}0.08, \tag{19}$$

where higher and lower values are also found in certain cases [51]. If this cluster baryon fraction is taken to be representative of the entire universe, and if one uses the BBN-indicated baryon density of Eq. (18), the cosmic dark-matter density appears to be less than the critical value 1, but the current evidence is not strong enough to definitively exclude $\Omega_{\mathrm{M}} = 1$ on these grounds. Still, a low-Ω universe is favored by a combination of the BBN baryon content of the universe and the high cluster baryon fractions, a finding sometimes referred to as the cluster ”baryon crisis.”

3.3 Structure Formation

Very dramatic constraints on the nature of dark matter arise from arguments of cosmic structure formation. At early times when the cosmic microwave background (CMB) radiation decoupled from the ambient plasma the universe was extremely smooth as demonstrated by the tiny amplitude of the temperature fluctuations of the CMB across the sky (Fig. 18). The present-day distribution of matter, on the other hand, is very clumpy. There are stars, galaxies, clusters of galaxies, and large-scale coherent structures on scales up to about $100\,\mathrm{Mpc}$. This is evident, for example, from the density map of Fig. 11 and also directly apparent from galaxy redshift surveys [53, 54]. The ”stick man” of the CfA redshift survey (Fig. 15) has become an icon for structure in the large-scale galaxy distribution. This picture shows the distribution of galaxy redshifts along a strip in the sky. Because redshifts measure distance through Hubble’s law (apart from the peculiar-motion component which cannot be removed without an independent distance indicator) this sort of representation gives one a direct visual impression of the three-dimensional galaxy distribution. A similar picture from the Las Campanas Redshift Survey is shown in Fig. 16 which goes out to much larger distances and thus demonstrates that there is large-scale structure, but also that there do not seem to be coherent structures on scales even larger than about $100\,\mathrm{Mpc}$. Therefore, it appears justified to think of the universe as homogeneous on the largest scales.

A perfectly homogeneous expanding universe stays that way forever; there will be no structures. The standard theory [4, 5, 55, 56] for the formation of structure assumes that the universe was initially almost, but not quite, perfectly homogeneous, with a tiny modulation of its density field. The action of gravity then works to enhance the density contrast as time goes on, leading to the formation of galaxies or clusters when the self-gravity of an overdense region becomes large enough to decouple itself from the overall Hubble expansion. Larger structures have not yet ”gone nonlinear” in this sense, yet the distribution of matter shows the result of the gravitational re-arrangement of the original distribution.

The outcome of this evolution depends on the initial spectrum of density fluctuations. The power spectrum of the primordial density field is usually taken to be approximately flat, i.e. of the ”Harrison-Zeldovich-type,” which corresponds to the power-law-index $n = 1$. However, the *effective* spectrum relevant for structure formation is the processed spectrum which obtains at the epoch when the universe becomes matter dominated as it is only then that fluctuations can begin to grow by the gravitational instability mechanism. Because the matter which makes up the cosmic fluid can diffuse, the smallest-scale primordial density fluctuations will be wiped out. This effect is particularly important if the density

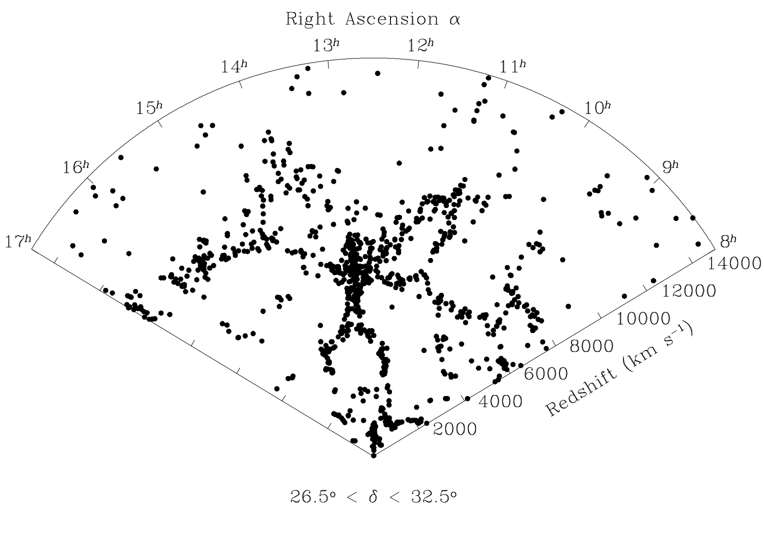

Fig. 15: ”A slice of the universe:” The galaxy distribution from the CfA redshift survey [52]. A redshift (apparent recession velocity) of $100\,\mathrm{km\,s^{-1}}$ corresponds to a distance of $h^{-1}\,\mathrm{Mpc}$. (Figure from Ref. [53].)

is dominated by weakly interacting particles which can diffuse far while they are relativistic. Low-mass particles stay relativistic for a long time and thus wipe out the primordial fluctuation spectrum up to large scales. Massive particles stay put earlier and thus have this effect only on small scales. One speaks of ”hot dark matter” (HDM) if the particle masses are small enough that all fluctuations are wiped out beyond scales which later correspond to a galaxy. Conversely, ”cold dark matter” (CDM) has this effect only on sub-galactic scales. In the CDM picture smallest structures form first (bottom-up) while in HDM large structures form first and later fragment into smaller ones such as galaxies (top-down).

One way of presenting the results of calculations of structure formation is to show the expected power-spectrum of the present-day matter distribution (Fig. 17) which can be compared to the observed galaxy distribution. The theory of structure formation then predicts the form, but not the amplitude of the spectrum which can be fit either on large scales to the observed temperature fluctuations of the cosmic

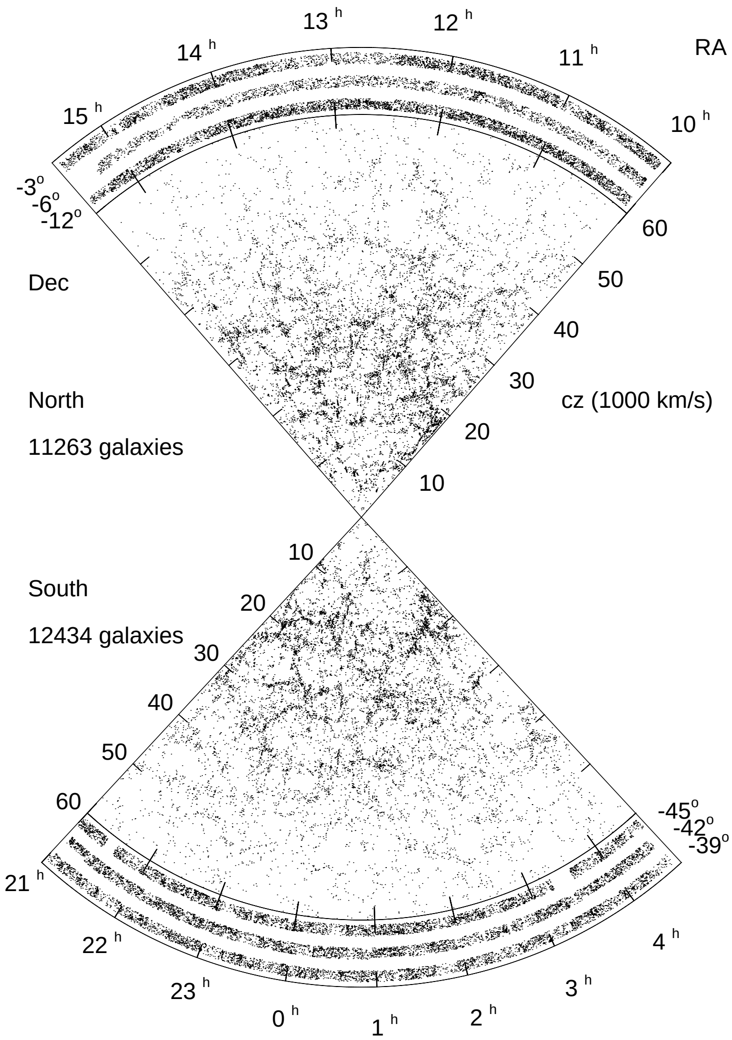

Fig. 16: The galaxy distribution from the Las Campanas Redshift Survey. The three slices in the northern and southern galactic caps are each shown projected on top of one another. (Figure courtesy of Huan Lin.)

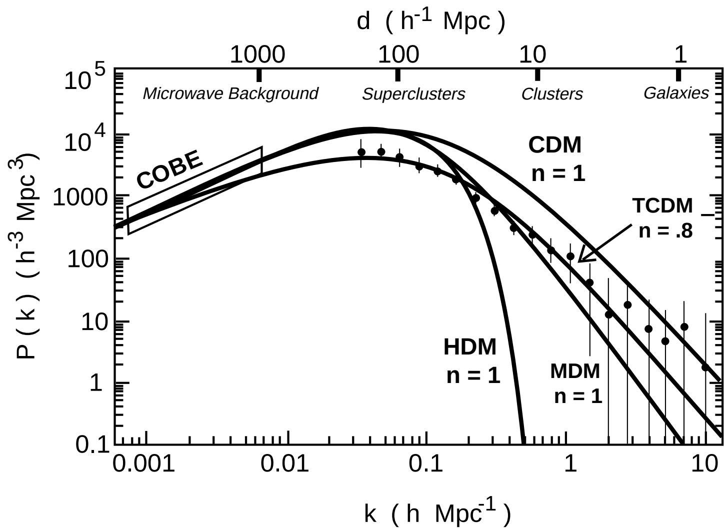

Fig. 17: Comparison of matter-density power spectra for cold dark matter (CDM), tilted cold dark matter (TCDM), hot dark matter (HDM), and mixed hot plus cold dark matter (MDM) for large-scale structure formation [57]. All curves are normalized to COBE and include only linear approximation; nonlinear corrections become important on scales below about $10\,\mathrm{Mpc}$.

microwave background as observed by the COBE satellite, or else on small scales to the observed galaxy distribution. Fig. 17 illustrates that hot dark matter (low-mass neutrinos) suppresses essentially all small-scale structure below a cut-off corresponding to a supercluster scale and thus does not seem to be able to account for the observations. While cold dark matter works impressively well, it has the problem of producing too much clustering on small scales. Ways out include a primordial power spectrum which is not strictly flat (tilted dark matter), a mix of cold and hot dark matter, or the assumption of a cosmological constant.

All of this leaves the question open where the primordial density fluctuations came from. The standard answer is provided by the inflationary-universe scenario which traces the density fluctuations to quantum fluctuations in the very early universe which were boosted to macroscopic scales during a phase of exponential expansion (inflation).

It is also possible that the original ”seeds” for structure formation are not density fluctuations of the primordial medium, but rather topological defects from a primordial phase transition such as ”textures” or ”cosmic strings” [59, 60]. However, such scenarios are now widely disfavored because the simplest gravitational instability picture works so well and because cosmic microwave observations already seem to rule out at least some variants of these theories [61].

Of course, the most important dark-matter question is if a purely baryonic universe is possible. Standard big-bang nucleosynthesis already negates this option, and structure formation yields further counter arguments. A primordial fluctuation spectrum in baryons consistent with the COBE measurements does not allow the observed structure to form until today. Weakly interacting particles fare better because they can begin to form structure earlier than baryonic matter which is held up by photon pressure until the time of decoupling (”dark matter boost”). One can circumvent this argument by preventing baryon density fluctuations from imprinting themselves on the cosmic microwave background (”isocurvature fluctuations”), leading to ”primordial isocurvature baryon” (PIB) scenarios. In view of the current cosmic microwave background observations, however, such scenarios seem to be essentially excluded [58].

Currently there is a wide consensus that some variant of a CDM cosmology where structure forms by gravitational instability from a primordial density fluctuations of the Harrison-Zeldovich type is probably how our universe works. Which does not mean, of course, that one should prematurely discard possible alternatives such as cosmic-string induced structure formation.

3.4 Cosmic Microwave Background

The cosmic microwave background radiation holds such a wealth of information that it has been rightly termed "The Cosmic Rosetta Stone" [62]. Its very presence in the universe and its uncannily precise black-body nature are the most striking proofs of the hot big-bang cosmogony. The observation of tiny angular temperature variations (Fig. 18) with typically $10\,\mu\mathrm{K}$ amplitudes already provides tight

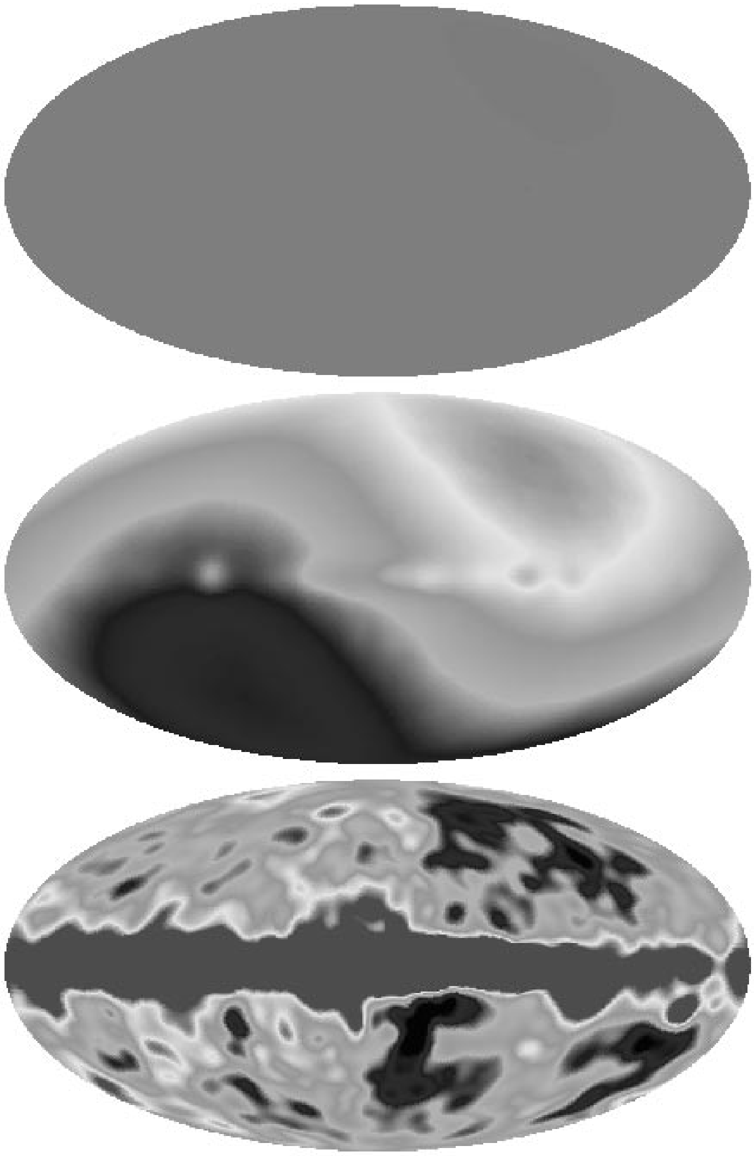

Fig. 18: Sky map of the temperature of the cosmic microwave background radiation in the $53\,\mathrm{GHz}$ band of the COBE satellite after four years of data taking [63]. *Top:* The dynamical range of the color coding is the temperature $T = 2.728\,\mathrm{K}$ of the cosmic microwave background, showing its almost perfect isotropy. *Middle:* Dynamical range is $\Delta T = 3.353\,\mathrm{mK}$ so that the apparent dipole distribution becomes visible which is attributed to the Doppler effect from our motion in the cosmic frame of reference. *Bottom:* $\Delta T = 18\,\mu\mathrm{K}$, showing tiny temperature fluctuations on all angular scales down to the resolution of the experiment. The galaxy occupies the horizontal central band; only the temperature fluctuations at sufficiently large galactic latitudes can be attributed to the cosmic microwave background rather than to galactic foreground emission.

constraints on theories of structure formation as outlined in the previous section. Since the first full-sky COBE maps appeared, a wealth of information from ground-based and balloon-borne measurements on smaller angular scales for patches of the sky have become available [64].

The important cosmological information is not contained in a coordinate-space sky map as in Fig. 18 but rather in its statistical properties. One usually considers the power spectrum of the temperature map in a spherical-harmonic expansion. Because of the overall cosmic isotropy one sums over all m for a given multipole order ℓ and analyses the power spectrum as a function of ℓ. In Fig. 19 the current data are shown together with theoretical predictions for a standard CDM universe. While there is still a lot of scatter in the data, they already seem to confirm the appearance of the first ”Doppler peak.” If structure forms by initial seeds such as textures or cosmic strings the predicted spectrum would not show acoustic peaks. Therefore, at least some variants of such models already seem to be ruled out [61].

The predicted pattern of the ”acoustic peaks” in the power spectrum is a direct manifestation of rather fine details of the cosmological model [65]. In Fig. 20 the theoretical predictions are shown for a standard and an open CDM model. One can easily see how conspicuously the pattern is shifted between the two models. There are two approved satellite missions, NASA’s Millimeter Anisotropy Probe (MAP) to be launched in 2000 and ESA’s Planck Surveyor to be launched around 2004 which will take full-sky temperature maps at much smaller angular resolutions than COBE could do. Fig. 20 also shows a set

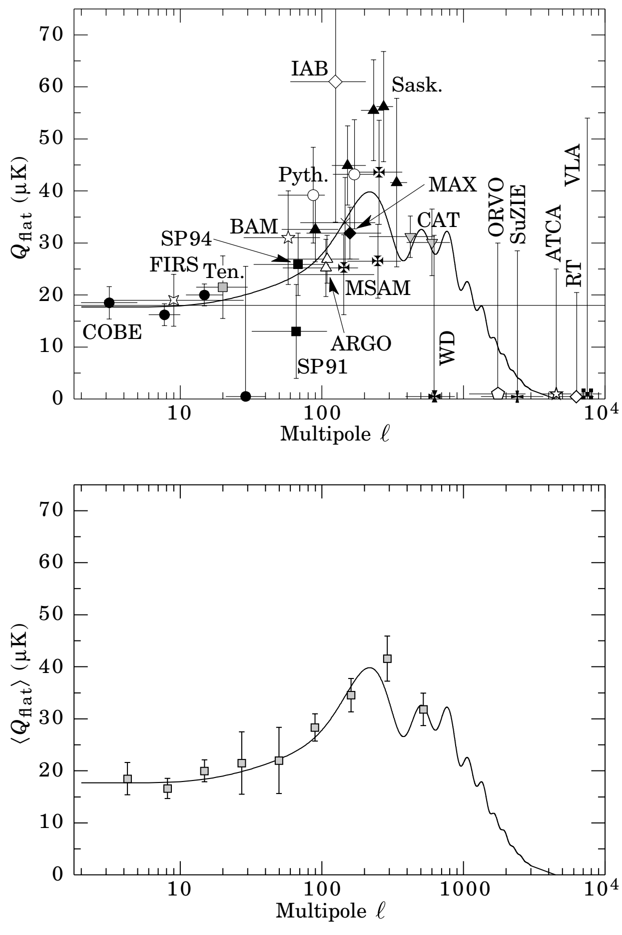

Fig. 19: Current status of CMB anisotropy observations from COBE and a large number of ground-based or balloon-borne experiments [64]. Plotted is the equivalent quadrupole moment of a sky map with a flat power spectrum of temperature fluctuations which provides the experimentally measured point at the angular scale of a given experiment. The theoretical curve corresponds to a standard CDM model with $\Omega_{\rm M}=1$, $\Omega_{\rm B}=0.05$, and $h=0.5$. The lower panel shows combined results for a number of angular bins. While this is not a statistically rigorous procedure it gives a good impression of the overall trend.

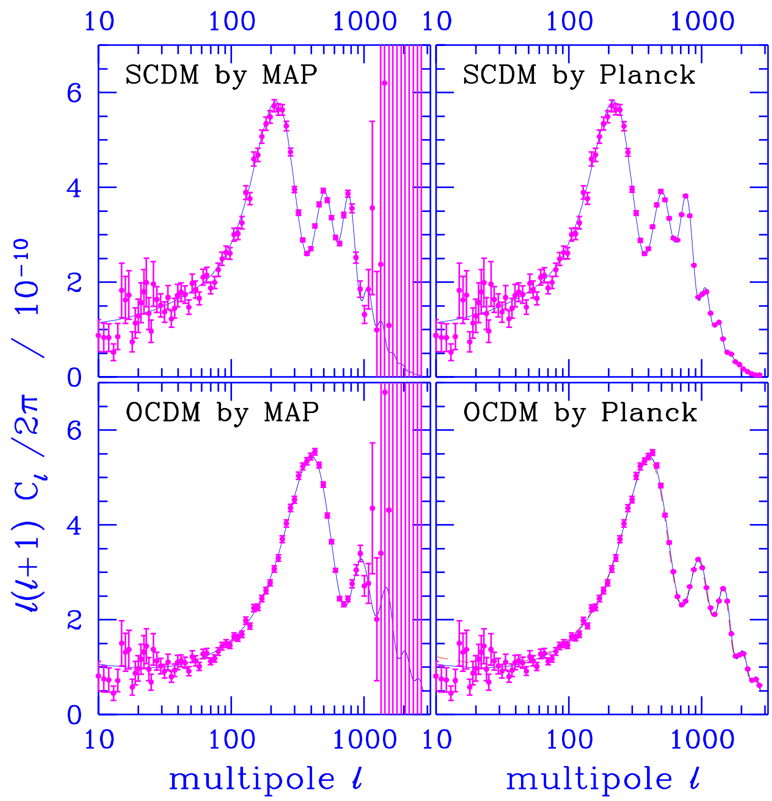

Fig. 20: Temperature power spectra for a standard CDM (SCDM) model with $\Omega_{\rm M} = 1$ and $h = 0.5$, and an open model (OCDM) with $\Omega_{\rm M} = 0.33$ and $h = 0.6$, each time without a cosmological constant [66]. Also shown are examples of expected data sets for simulated CMB sky maps.

of simulated measurement results for both MAP and Planck if the SCDM or OCDM models happen to represent our universe. Evidently the cosmological parameters can be pinned down with great precision. It is thought that these experiments will be able to determine the most important cosmological parameters eventually on the 1% level, notably the baryon fraction and total dark matter content [67]. There remain degeneracies between different combinations of parameters, however, which will need to be broken by other methods.

4 CANDIDATES AND SEARCHES

4.1 Dark Stars (MACHOs)

The existence of huge amounts of dark matter in the universe at large and in our own galaxy in particular is now established beyond any reasonable doubt, but its physical nature remains an unresolved mystery. A number of compelling arguments relating to big-bang nucleosynthesis, the amount of x-ray gas in galaxy clusters, and the small CMB anisotropies in conjunction with theoretical structure-formation arguments negate the possibility of a purely baryonic universe. However, there is a big difference between compelling yet circumstantial arguments and a direct proof. Therefore, one may still ask if the galactic dark halo could at all consist of purely baryonic material in some nonluminous form, and if so, how one should go about to detect it. Moreover, the same arguments which indicate that the universe is not purely baryonic motivate significant amounts of dark baryons which must be hiding somewhere.

Assuming there are dark baryons in the galactic halo, which form could they take? Evidently they are not in the form of normal and thus luminous stars or in the form of hot (and thus shining) or cold (and thus absorbing) gas or dust. In terms of stellar objects one is thus left with stars which are too small to shine brightly (brown dwarfs or M-dwarfs) or with burnt-out stellar remnants (white dwarfs, neutron stars, black holes). Stellar remnants seem implausible because they arise from a population of normal stars of which there is no trace in the halo. Neutron stars or black holes, in particular, typically would form in supernova explosions of which there cannot have been too many in the galaxy without contaminating it with ”metals,” i.e. elements heavier than hydrogen and helium. The overproduction of helium also constrains the presence of white dwarfs which are remnants of stars not massive enough to reach the supernova phase. White dwarfs as a dominant halo component cannot be rigorously excluded. However, besides the problem of the helium overproduction they would require an extremely special stellar initial mass function (IMF) with masses strongly peaked between 2 and $8\,M_\odot$ (solar mass) to avoid the overproduction of supernovae (for heavier masses) and of normal stars which would still shine today. These sort of arguments are explained in more detail in Refs. [68, 69].

For small stars one distinguishes between M-dwarfs with a mass below about $0.1\,M_\odot$ which are intrinsically dim and brown dwarfs with $M \lesssim 0.08\,M_\odot$ which never ignite hydrogen and thus shine even more dimly from the residual energy due to gravitational contraction. The stellar mass function rises towards small masses (most stars are small) so that one expects significant numbers of such obejcts in the galaxy. However, if the galactic halo were to consist of dim stars would leave one wondering why this population contains so few higher-mass and thus luminous stars which form so easily in the disk. In any event, very long-exposure images of the Hubble Space Telescope restrict the possible M-dwarf contribution of the galactic halo to below 6% [70].

An extrapolation of the stellar mass function to small masses predicts large numbers of brown

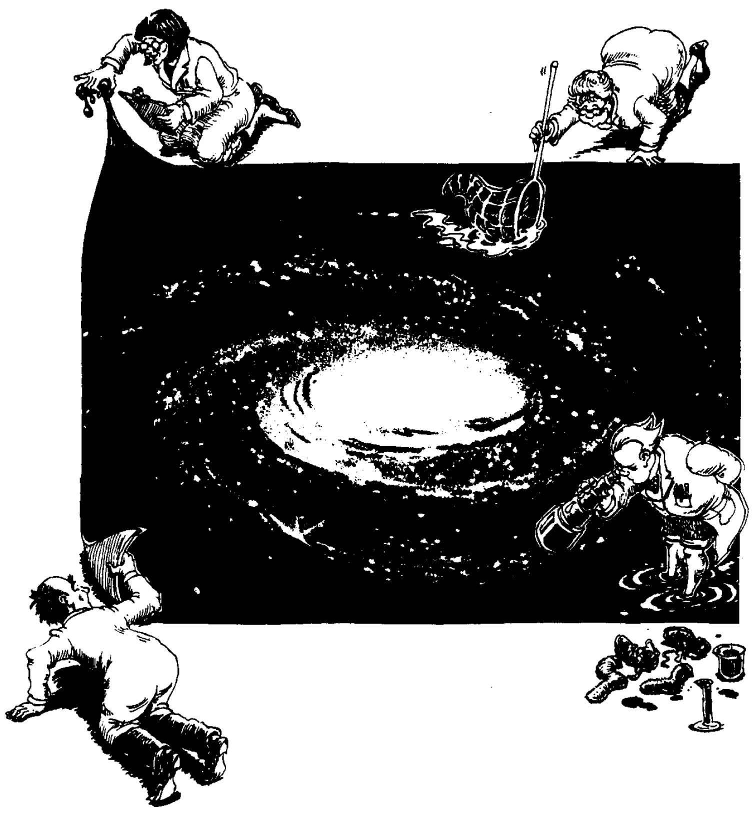

Fig. 21: The search for dark matter in the Milky Way. Reprinted with permission of David Simonds (c).

dwarfs within normal stellar populations, but their very existence has been difficult to prove [71] with only one firm candidate now established [72]. While the paucity of luminous stars in the galactic halo argues against brown dwarfs, they are the most plausible baryonic candidate for the galactic dark matter [68]. This conclusion can be avoided if the halo is very clumpy, allowing for the possibility of gravitationally bound clouds of molecular hydrogen which are very difficult to detect and perhaps clumps of dim stars [73].

Whatever the merits of the arguments for or against baryonic objects as galactic dark matter, nothing would be more convincing than a direct detection of the candidates or their exclusion in a search experiment. Fortunately, in 1986 Paczyński proposed an exciting method to search systematically for faint stars in the halo of our galaxy [74]. His idea is based on the well-known effect [75] that a ”pointlike” mass (deflector) placed between an observer and a light source creates two distinct images as indicated in Fig. 22. (A nonsingular and transparent mass distribution always yields an odd number of images.) When the source is exactly aligned behind the deflector (mass $M_{\rm D}$) the image would be an annulus instead (”Einstein ring”) with a radius (”Einstein radius”) of

$$r_{\rm E} = \sqrt{G_{\rm N} M_{\rm D} d} \qquad \text{where} \qquad d \equiv \frac{4 d_1 d_2}{d_1 + d_2} \tag{20}$$

with the distances $d_{1,2}$ as in Fig. 22. Because of differential bending of the ”rays” which produce the images, the image brightnesses will be different from each other and from the single image in the absence of gravitational lensing. If the two images cannot be separated because their angular distance α is below the resolving power of the observer's telescope, the only effect will be an apparent brightening of the star, an effect known as ”gravitational microlensing.” The magnification (”amplification”) factor is

$$A = \frac{2 + u^2}{u\sqrt{4 + u^2}} \qquad \text{where} \qquad u \equiv \frac{r}{r_{\rm E}} \tag{21}$$

and r is the distance of the deflector from the line of sight.

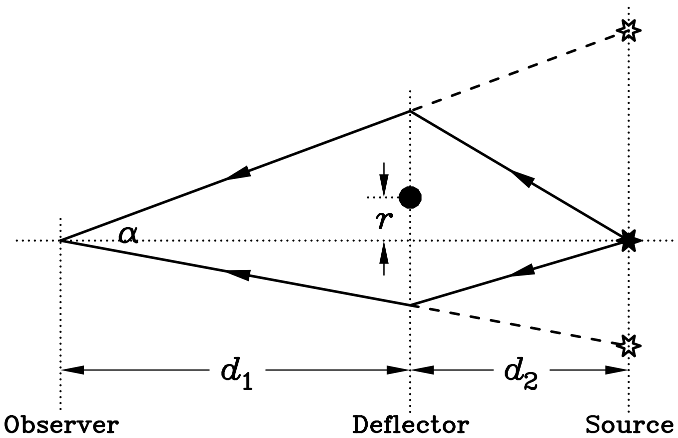

Fig. 22: Geometry of light deflection by a pointlike mass which yields two images of a source viewed by an observer.

If we imagine a terrestrial observer watching a distant star, and if the galactic halo is filled with ”massive astrophysical halo objects” (MACHOs), one of them will occasionally pass near the line of sight and thus cause the image of the monitored star to brighten. If the deflector moves with the velocity v transverse to the line of sight, and if its ”impact parameter” (minimal distance to the line of sight) is b, then one expects an apparent lightcurve as shown in Fig. 23 for several values of $b/r_{\rm E}$. The natural ”unit of time” is $r_{\rm E}/v$, the origin was chosen at the time of closest approach to the line of sight.

A convenient sample of target stars is provided by the Large Magellanic Cloud (LMC) which is a small satellite galaxy of the Milky Way at a distance from us of about $50\,{\rm kpc}$. It has enough bright stars,

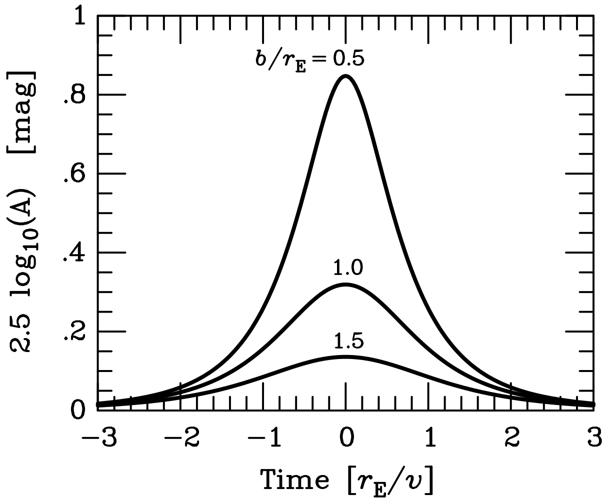

Fig. 23: Apparent lightcurve of a source if a pointlike deflector passes the line of sight with a transverse velocity v and an "impact parameter" b. The vertical axis for the magnification ("amplification") factor A was chosen logarithmically and multiplied with 2.5 to obtain the usual astronomical logarithmic brightness measure "magnitude" or mag.

it is far enough away so that the line of sight intersects a significant fraction of the galactic halo, and it is far enough above the galactic plane so that one actually cuts through the halo, not just through the galactic disk. Any given star in the LMC will be substantially brightened at the time of observation if the line of sight intersects with the circular cross section πr_E^2 around some MACHO. If the halo is supposed to be made of such objects, their number density is inversely proportional to their assumed mass while πr_E^2 is directly proportional to it. Therefore, the probability for a target star to be lensed at the instance of observation is independent of the mass of the dark-matter objects. For stars in the LMC one finds a probability ("optical depth for microlensing of the galactic halo") of $\sim 10^{-6}$. Put another way, if one looks simultaneously at $\sim 10^6$ stars in the LMC one has a good chance of seeing at least one of them brightened by a dark halo star.

In order to recognize a lensing event one has to monitor this large sample of stars long enough to identify the characteristic lightcurve shown in Fig 23. It has the property of being unique, symmetric about $t = 0$, and achromatic, three signatures which allow one to discriminate against normal variables which comprise about 1% of all stars. The typical duration of the apparent brightness excursion is r_E/v, i.e. the time it takes a MACHO to cross an Einstein radius, which depends on the MACHO mass. If the deflector mass is $1\,M_\odot$ (solar mass) a mean microlensing time will be 3 months, for $10^{-2}\,M_\odot$ it is 9 days, for $10^{-4}\,M_\odot$ it is 1 day, and for $10^{-6}\,M_\odot$ it is 2 hours.

The microlensing search for dark stars was taken up by the MACHO and the EROS collaborations, both reporting first tentative candidates toward the LMC in 1993 [76]; the lightcurves for the first three MACHO candidates are shown in Fig. 24. Because one did not expect the galactic halo to consist dominantly of dark stars these findings were quite sensational at the time. Meanwhile, more candidates have appeared, perhaps a dozen or so toward the LMC. Moreover, the galactic bulge has been used as another target where many more events occur through microlensing by ordinary disk stars. While observations of the galactic bulge are not sensitive to halo dark-matter stars, they allow one to develop a good understanding of the microlensing technique itself, and anyhow are interesting as a method to study the structure of the galactic bulge and disk and their stellar content. It is now established beyond doubt that the microlensing technique works. Within the past few years it has established itself as a completely new approach to galactic astronomy, with at least half a dozen collaborations pursuing observations of various target regions. As a by-product these searches naturally produce a huge database of intrinsically variable stars which is invaluable to stellar astronomy, independently of the dark-matter problem.

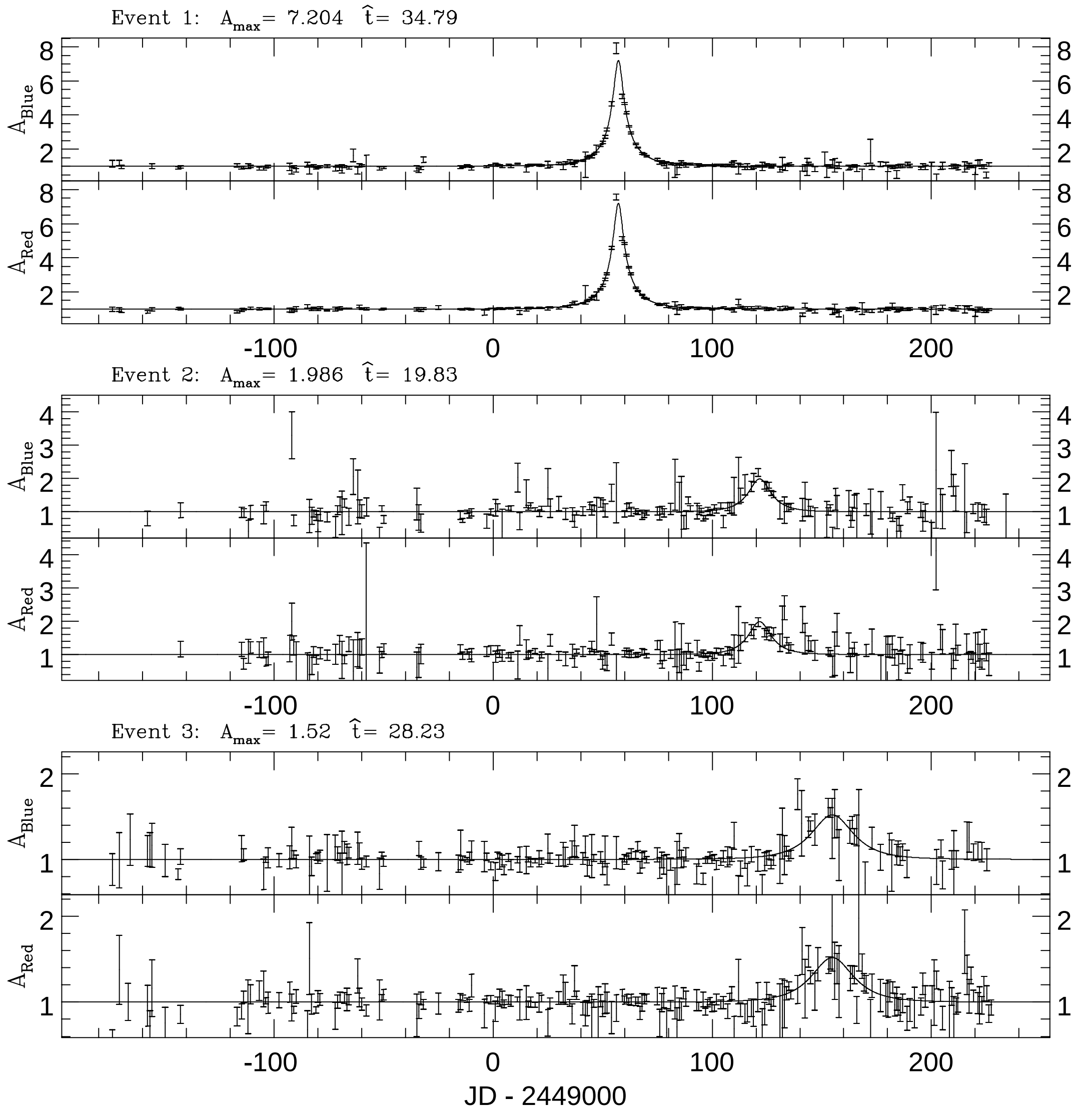

Fig. 24: Red and blue lightcurves (amplification factors) of the first three microlensing candidates of the MACHO collaboration toward the LMC [77]. The horizontal axis (time) is measured in days with the zero point at Julian Day 2449000, corresponding to January 12, 1993.

Far from clarifying the status of dim stars as a galactic dark matter contribution, the results of the current microlensing results toward the LMC are quite confusing [77, 78, 79, 80]. If one assumes a standard spherical galactic halo the absence of short-duration events excludes a large range of MACHO masses as a dominant halo component (Fig. 25). On the other hand, assuming all MACHOs have the same mass one finds a best-fit mass of about $0.4\,M_\odot$ and a halo fraction which could be anything between about 10% and 100% (Fig. 25). The best-fit mass is characteristic of white dwarfs, but a galactic halo consisting primarily of white dwarfs is highly implausible and barely compatible with a variety of observational constraints. On the other hand, if one wanted to attribute the observed events to brown dwarfs ($M \lesssim 0.08\,M_\odot$) one needs to appeal to a very nonstandard density and/or velocity distribution of these objects. Other explanations involve an unexpectedly large lensing contribution from LMC stars, a thick galactic disk contribution, an unrecognized population of normal stars on the line of sight to the LMC, and other speculations, with pros and cons for each hypothesis [81]. At the present time it is absolutely unclear which sort of objects the microlensing experiments are seeing toward the LMC and where the lenses are.

Meanwhile a first event has appeared in both the MACHO and EROS data toward the Small Mag-

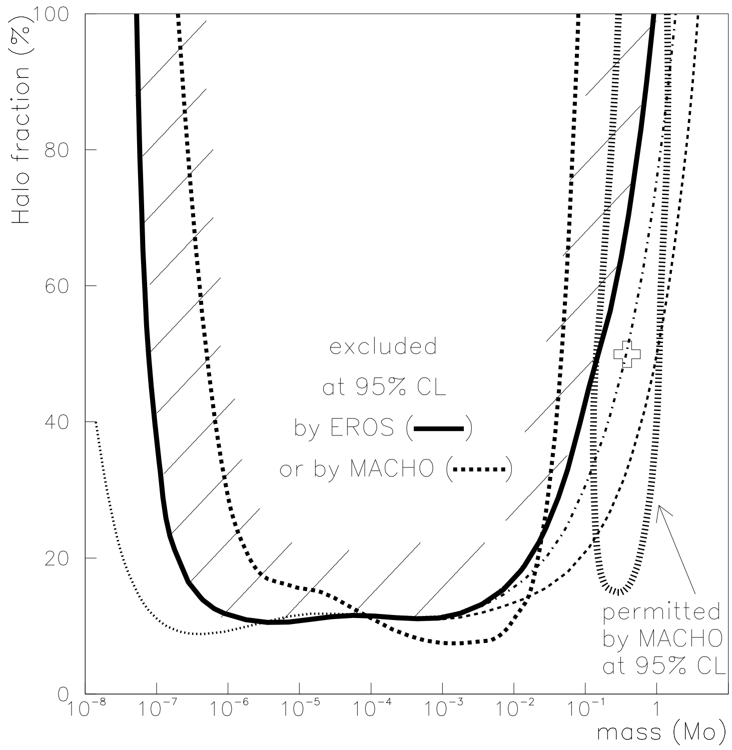

Fig. 25: Exclusion diagram at 95% C.L. for the halo fraction and mass of the assumed MACHOs [79]. It was assumed that they all have the same mass and that a standard model for the galactic halo obtains. The dotted line on the left is the limit when blending and finite size effects are ignored in the EROS limits. The dot-dashed and dotted lines on the right are the EROS limits when 1 or 2 of their candidate events are attributed to MACHOs. The cross is centered on the 95% C.L. permitted range of the MACHO collaboration for their case of a standard spherical halo [80].

ellanic Cloud (SMC) [82], another galactic satellite at a slightly larger distance than the LMC and about 20° away in the sky. While one event does not carry much statistical significance, its appearance is consistent with the LMC data if they are interpreted as evidence for halo dark matter. However, this interpretation would imply a large mass (a few solar masses) for the lens due to the large duration.

Besides more data from the LMC and SMC directions, other lines of sight might provide significant information on the stellar make-up of the galactic halo. Of particular importance is the Andromeda galaxy (Fig. 2) as a target because the line of sight cuts through the halo almost vertically relative to the galactic disk. Unfortunately, Andromeda is so far away that one cannot resolve individual target stars for the microlensing purpose. One depends on the ”pixel lensing” technique where one observes the apparent brightening of a single pixel of the CCD camera; one pixel covers the unresolved images of many stars. At least two groups pursue this approach which already has produced preliminary limits [83].

4.2 Neutrinos

In spite of the puzzling observation of microlensing events toward the Large and Small Magellanic Clouds which may indicate that some of the galactic dark matter is in the form of dim stars, the case for a dominant dark-matter component in the form of weakly interacting particles is rather compelling. A purely baryonic universe is at odds with the baryon fraction implied by big-bang nucleosynthesis and the amount of x-ray gas in galaxy clusters. Most importantly, the formation of structure by the generic gravitational instability mechanism does not work with baryons alone, while it is impressively successful with weakly interacting particles as dark matter.

The only candidates which are currently known to exist are neutrinos. In order to understand if

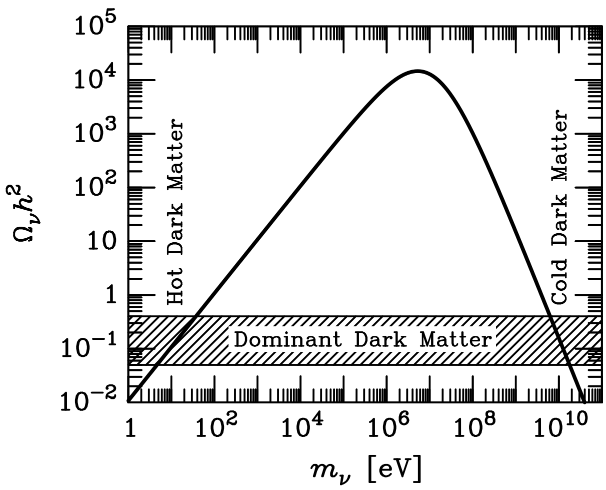

Fig. 26: Cosmic neutrino mass density as a function of neutrino mass. The hatched band indicates the range for Ωh^2 which the dominant particle dark matter component must provide according to Eq. (24).

they could represent the dark matter we need to calculate their cosmic abundance as a function of their assumed mass. If it is small this is a straightforward exercise; in the framework of the hot big-bang cosmogony one expects about as many cosmic "black-body neutrinos" as there are microwave photons. In detail, the cosmic energy density in massive neutrinos is found to be $\rho_\nu = \frac{3}{11}\, n_\gamma \sum m_\nu$ with n_γ the present-day density in microwave background photons [5]. The sum extends over the masses of all sequential neutrino flavors. In units of the critical density this is (Fig. 26)

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}. \tag{22}$$

The observed age of the universe together with the measured expansion rate yields $\Omega h^2 \lesssim 0.4$ so that for any of the three families

$$m_\nu \lesssim 40\,\mathrm{eV}. \tag{23}$$

This mass limit is probably the most important astrophysical contribution to neutrino physics because for ν_τ it improves the experimental limit by about six orders of magnitude.

It is also interesting to ask for a lower limit on Ωh^2 which the dominant dark-matter component must obey. According to Eq. (14) the matter density is limited by $\Omega_\mathrm{M} \gtrsim 0.3$. Allowing for a significant baryon fraction indicates that particle dark matter (PDM) should obey $\Omega_\mathrm{PDM} \gtrsim 0.2$. Taking $h \gtrsim 0.5$ as a lower limit for the expansion rate implies

$$0.05 \lesssim \Omega_\mathrm{PDM} h^2 \lesssim 0.4 \tag{24}$$

as a reasonable range where a given particle dark matter candidate could be all of the nonbaryonic dark matter (hatched band in Fig. 26). Therefore, neutrinos with a mass $4\,\mathrm{eV} \lesssim m_\nu \lesssim 40\,\mathrm{eV}$ could represent all of the nonbaryonic dark matter.

There is a second solution at large masses. If the mass significantly exceeds the cosmic temperature at a given epoch, the neutrino density is suppressed by a Boltzmann factor $e^{-m_\nu/T}$. The weak interaction rates in the early universe become slow relative to the overall expansion when the temperature falls below about $1\,\mathrm{MeV}$. For masses exceeding this weak freeze-out temperature the Boltzmann suppression occurs while the neutrinos are still in thermal equilibrium, reducing the relic density accordingly. A detailed calculation of the relic density requires an approximate solution of the Boltzmann collision equation [5]. Apart from a logarithmic correction one finds $\Omega_\nu h^2 \propto m_\nu^{-2}$ as shown in Fig. 26 for the Majorana case. Dirac neutrinos have a slightly smaller relic density, but in either case neutrinos could be the dark matter if their mass was a few GeV. The laboratory limit for ν_τ of about $20\,\mathrm{MeV}$, and more restrictive ones for ν_μ and ν_e, precludes this possibility among the known sequential flavors.

Low-mass neutrinos, however, are problematic dark matter candidates from the perspective of structure formation because they represent ”hot dark matter” (Sec. 3.3). Forming small-scale structure such as galaxies would probably require topological defects such as cosmic strings as seeds for the gravitational instability, and even then a scenario consistent with cosmic microwave background constraints may not be possible.

In addition there is a well-known problem with neutrinos filling the dark-matter haloes of galaxies. By definition, galactic dark-matter neutrinos would be gravitationally bound to the galaxy so that their velocity would be bound from above by the galactic escape velocity $v_{\rm esc}$, yielding an upper limit on their momentum of $p_{\rm max} = m_\nu v_{\rm esc}$. Because of the Pauli exclusion principle the maximum number density of neutrinos is given when they are completely degenerate with a Fermi momentum $p_{\rm max}$, i.e. it is $n_{\rm max} = p_{\rm max}^3/3\pi^2$. Therefore, the maximum local mass density in dark-matter neutrinos is $m_\nu n_{\rm max} = m_\nu^4 v_{\rm esc}^3/3\pi^2$. As this value must exceed a typical galactic dark matter density, one obtains a *lower* limit on the necessary neutrino mass. A refinement of this simple derivation is known as the Tremaine-Gunn limit [9]; for typical spiral galaxies it is about $20\,\mathrm{eV}$ [84].

Therefore, dark-matter neutrino masses are squeezed between the upper limit from the overall cosmic mass density, and the lower limit from the galactic phase-space argument. They are squeezed, but perhaps not entirely squeezed out. Neutrinos could not be the dark matter of dwarf galaxies where a mass of a few $100\,\mathrm{eV}$ is required by the Tremaine-Gunn argument [84]. However, perhaps the dark matter in dwarf galaxies is of a different physical nature. At any rate, the galactic phase-space argument surely disturbs any simple-minded fantasy about neutrinos being the dark matter on all scales.

Neutrinos may still play an important role as dark matter and for structure formation if they are a subdominant component of a cold-dark matter (CDM) universe. It was discussed in Sec. 3.3 that CDM produces too much small-scale structure if the primordial density fluctuation spectrum was of the Harrison-Zeldovich type. This problem can be patched up by invoking a mixed hot plus cold dark matter (MDM or CHDM) cosmology where the hot component erases enough of the initial power on small scales to compensate for the overproduction by pure CDM [85]. In a flat universe ($\Omega = 1$) the best fit is obtained with a total mass in neutrinos corresponding to $\sum m_\nu = 5\,\mathrm{eV}$ with an equipartition of the masses among the flavors.

The high baryon fraction of galaxy clusters (Sec. 3.2) provides another motivation for a neutrino dark matter component. If clusters represent a fair sample of the cosmic matter inventory their high baryon fraction points to a low-Ω universe. However, neutrinos are naturally more dispersed than CDM, providing a less-clustered dark matter background, somewhat alleviating the cluster baryon problem [86].

It will be very difficult to test this hypothesis. A direct detection of cosmic background neutrinos does not seem to be realistic in the foreseeable future whether or not they have masses. It is possible, of course, that the requisite neutrino mass will appear in neutrino oscillation experiments; tentative evidence has already been reported by the LSND Collaboration [87]. The interpretation of their $\bar\nu_e$ excess counts in terms of neutrino oscillations implies a ν_e-ν_μ mass difference of order $1\,\mathrm{eV}$ or more, pointing to cosmologically significant neutrino masses. At the present time one has to wait and see if more LSND data and other experiments, notably KARMEN [88], will confirm this claim.

The LSND claim is not easily compatible with the much smaller neutrino mass differences indicated by the oscillation interpretation of the solar and atmospheric neutrino anomalies. Of course, oscillation experiments give us information only about the *differences* of neutrino masses, not about their absolute values. Therefore, even if these differences are small, all neutrinos could have approximately equal masses with a common offset from zero which could be much larger than their mass differences. Such scenarios of ”degenerate neutrino masses” are not testable by oscillation experiments so that the direct searches for a ν_e mass in the eV range by tritium β-spectrum experiments and by neutrinoless

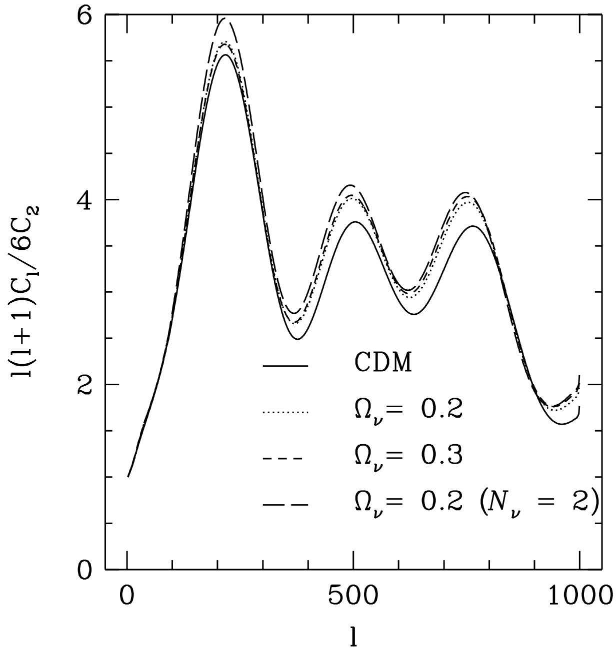

Fig. 27: Power spectrum of the temperature sky map for the cosmic microwave background in a cold dark matter cosmology, and three variants of mixed dark matter [90].

$\beta\beta$-decay experiments remain of great importance. Similarly, the observation of a neutrino signal from a galactic supernova by a detector like Superkamiokande or the proposed OMNIS [89] would allow one to detect or exclude sub-eV electron neutrino masses.

In Sec. 3.4 we discussed the enormous power of future cosmic micrwave background observations to distinguish between different cosmological models. Could one distinguish a pure CDM from a CHDM universe? In Fig. 27 the expected power spectrum of the angular temperature fluctuations is shown for a CDM scenario as a solid line. The modified power spectra for three versions of CHDM cosmologies are also shown. The resolution expected from the future microwave satellites is better than the differences between these curves. However, there are other unknown parameters such as the overall mass density, the Hubble constant, the cosmological constant, the baryon fraction, and so forth, which all affect the expected power spectrum. All of them have to be determined by fitting the power spectrum to the observations, leading to "degeneracies" in the sense that not all of these parameters can be determined independently. Therefore, it is probably not possible to identify a small neutrino component by the microwave data alone. However, in conjunction with the expected precision measurement of the power spectrum of the matter density from the upcoming Sloan Digital Sky Survey one would be sensitive to sub-eV neutrino masses, and even a mass as small as $0.1\ \mathrm{eV}$ would make a nonnegligible difference [91].

4.3 Weakly Interacting Massive Particles (WIMPs)

Baryons apparently do not make up the bulk of the cosmic matter. Massive neutrinos are the only alternative among the known particles, but they are essentially ruled out as a universal dark-matter candidate, even if they may play an important role as a hot component in a universe which is otherwise dominated by cold dark matter. What is the physical nature of this dominant component?

From the discussion in the previous section and from Fig. 26 it is apparent that neutrinos with a mass of a few GeV could well play this role. Their relic abundance would be appropriate for the cosmic dark matter density, and their large mass would guarantee that they became nonrelativistic more than early enough to avoid the erasure of primordial density fluctuations: they would be cold dark matter. While the experimental mass limits prevent ν_e, ν_μ or ν_τ to play this role, a fourth-generation neutrino was a possibility until the CERN measurements of the Z^0 width showed that there are exactly 3 neutrino families with $m_\nu \lesssim \frac{1}{2}m_Z = 46\,\mathrm{GeV}$. With a mass exceeding this limit the relic abundance would be too low (Fig. 26).

The calculation of the relic density which leads to the curve of Fig. 26 assumes that heavy neutrinos actually can annihilate with each other, i.e. that there are equal numbers of neutrinos and antineutrinos in the early universe. For Majorana neutrinos which are their own antiparticles this represents no extra constraint, but for Dirac neutrinos this assumption cannot be taken for granted. After all, the normal matter in the universe survives its own primordial annihilation only because of the baryon asymmetry of the universe, and a similar asymmetry could exist in the neutrino sector. Because of the unknown cosmic asymmetry the relic density of Dirac neutrinos is not calculable so that one might think that a fourth-generation Dirac neutrino with a mass beyond the Z^0-decay limit could well play the role of cold dark matter. However, this possibility is excluded by the direct experimental searches for galactic dark matter to be discussed below. (As we shall see their scattering cross section is coherently enhanced so that they are easier to detect than Majorana neutrinos.) Either way, a heavy fourth-generation neutrino would have seemed implausible anyway because the particles comprising the dark matter must be stable on the scale of the age of the universe of about $10\,\mathrm{Gyr}$. There would have been no reason to expect a massive fourth-generation neutrino to be so long-lived.

However, something like a stable heavy neutrino, a generic *Weakly Interacting Massive Particle (WIMP)*, still seems like a good possibility because an annihilation cross section given roughly by the weak scale leaves us with the right relic density and a mass appropriate for cold dark matter. Naturally, these particles must couple to Z^0 more weakly than sequential neutrinos or else they, too, would be excluded by the measured Z^0 decay width. Fortunately, supersymmetric extensions of the particle-physics standard model naturally motivate the existence of the requisite particles in the form of neutralinos [26].

Supersymmetric extensions of the standard model predict a doubling of the existing particles in that every bosonic degree of freedom is matched by a supersymmetric fermionic one and vice versa. Normal and supersymmetric particles differ by a quantum number called R-parity which may be conserved so that the lightest supersymmetric particle (LSP) would have to be stable. If the LSP is the lightest "neutralino," i.e. the lightest mass eigenstate of a general superposition of the neutral spin-$\frac{1}{2}$ fermions expected in this theory, namely the photino (spin-$\frac{1}{2}$ partner of the photon), Zino (spin-$\frac{1}{2}$ partner of the Z^0 boson), and Higgsino (spin-$\frac{1}{2}$ partner of a neutral Higgs boson), then we have a perfect ersatz neutrino available. Neutralinos are Majorana fermions so that their cosmic relic density is determined by the freeze-out from thermal equilibrium along the lines of Fig. 26 rather than by an unknown cosmic particle-antiparticle asymmetry. Their interactions would be roughly, but not exactly, of weak strength. In detail their annihilation and scattering cross sections depend on specific assumptions about a given supersymmetric model and on the values of various parameters within such models.

At the present time no empirical evidence exists that supersymmetric extensions of the standard model are indeed realized in nature; of course the search for supersymmetric particles is one of the prime goals for experiments at future accelerators such as the LHC. For the time being the cosmological need for a suitable cold dark matter candidate is the strongest empirical hint for the reality of the supersymmetric doubling of the elementary particle zoo. The nonobservation of supersymmetric particles at current accelerators places stringent limits on the neutralino mass and interaction cross section [92].

In the mid-1980s in became clear that even though WIMPs are by definition weakly interacting particles one can search for them in our galaxy by a variety of methods [26, 93, 94, 95, 96]. The "direct" approach relies on elastic WIMP collisions with the nuclei of a suitable target, for example a germanium crystal. Dark-matter WIMPs move with a typical galactic virial velocity of around $300\,\mathrm{km\,s^{-1}}$. If their mass is $10-100\,\mathrm{GeV}$ their energy transfer in such an elastic collision would be of order $10\,\mathrm{keV}$. Therefore, the task at hand is to identify such energy depositions in a macroscopic sample of a target substance. Of the many ways that have been discussed to achieve this goal, three are of particular importance. First, one may search for scintillation light, for example in NaI crystals or in liquid xenon. Second, one may search for an ionization signal in a semiconductor, notably in a germanium crystal. Third, one may cool the target (for example a sapphire crystal) to very low temperatures of order $10\,\mathrm{mK}$ so that a $10\,\mathrm{keV}$ energy deposition causes a measurable temperature increase. This ”cryogenic” or ”bolometric” approach employs a variety of methods to measure this heating, for example a superconducting strip attached to the target which is shifted toward the normal conducting phase by the temperature increase.

The main problem with any such experiment is the extremely low expected signal rate. In detail it depends on the assumed WIMP properties and target material, but a typical number is below $1\,\mathrm{event}\,\mathrm{kg}^{-1}\,\mathrm{day}^{-1}$, a counting-rate unit usually employed in this field. To reduce natural radioactive contaminations one must use extremely pure substances and to reduce the background caused by cosmic rays requires these experiments to be located deeply underground, for example in the Gran Sasso laboratory or the Boulby salt mine in England. All current experiments are essentially background limited at a level of the order $1\,\mathrm{event}\,\mathrm{kg}^{-1}\,\mathrm{day}^{-1}$.

Neutrinos scatter on nucleons by virtue of a vector-current and an axial-vector current (spin-dependent) interaction. For the small momentum transfers imparted by galactic WIMPs such collisions are essentially coherent over an entire nucleus, leading to an enhancement of the effective cross section. The relatively large detection rate expected in this case allowed one in the late 1980s to exclude fourth-generation Dirac neutrinos for the galactic dark matter [94].

However, for Majorana neutrinos the vector-current interaction vanishes identically; they interact only by a spin-dependent force. The coherence over the nucleus now works in the opposite direction: essentially it is the total spin of the nucleus which is relevant for the scattering rate rather than the scattering rates summed over the individual nucleons. Therefore, Majorana neutrinos are much more difficult to detect. Because neutralinos are of the Majorana type one largely depends on their spin-dependent interaction cross section even though they may have a scalar-exchange contribution, unlike proper neutrinos which interact only by the exchange of vector bosons.

Currently the best limits on WIMP scattering cross sections come from several germanium experiments [97], the NaI scintillation detectors of the United Kingdom Dark Matter Collaboration (UKDMC) located in the Boulby salt mine in England [98] and of the DAMA experiment located in the Gran Sasso National Laboratory near Rome in Italy [99]. In Fig. 28 the current limits for the spin-independent scattering cross section are shown in the usual normalization as a cross section per nucleon which is the only practical method to compare results from experiments with different target materials. What is also shown as a shaded region is the detection rate expected for neutralinos in the minimal superymmetric standard model (MSSM) without universal scalar mass unification [100, 101].

Intruigingly, the current experiments already touch the parameter space expected for supersymmetric particles and thus are in a position where they begin to have a real chance of actually detecting dark matter. One problem is, of course, how one could attribute a tentative signal unambiguously to galactic WIMPs rather than some unidentified radioactive background. One signature is the annual signal modulation which arises because the Earth moves around the Sun while the Sun orbits around the center of the galaxy. Therefore, the net speed of the Earth relative to the galactic dark matter halo varies, causing a modulation of the expected counting rate because of the modulation of the effective WIMP velocity distribution seen by the detector. The DAMA/NaI experiment has actually reported tentative evidence for such a modulation [104] which would point to neutralinos just below their previous exclusion range [105]. At the present time the significance of this signature is very low, and tentative signals are bound to appear just below the previous exclusion ranges. Still, the good news is that this tentative claim *could* be true in the sense that one has reached the sensitivity necessary to find supersymmetric dark matter.

In the near future large-scale cryogenic detectors will explore a vast space of WIMP-nucleon cross-sections. The CRESST experiment [102] (Fig. 29) which is located in the Gran Sasso underground laboratory aims at relatively low WIMP masses with a sensitivity goal indicated by the dotted line in Fig. 28. It uses sapphire crystals as targets and a purely bolometric technique to measure the heat de-

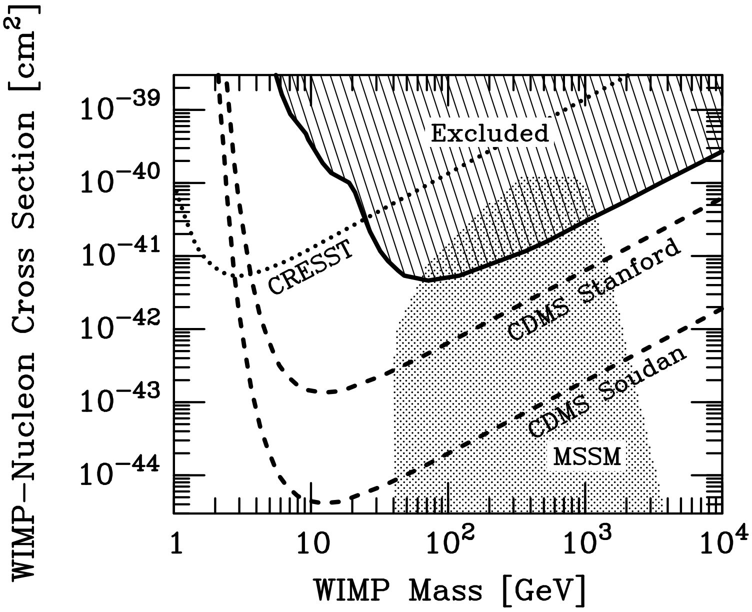

Fig. 28: Exclusion range for the spin-independent WIMP scattering cross section per nucleon from the NaI experiments [98, 99] and the germanium detectors [97]. Also shown is the range of expected counting rates for neutralinos in the minimal supersymmetric standard model (MSSM) without universal scalar mass unification [100, 101]. The search goals for the upcoming large-scale cryogenic experiments CRESST [102] and CDMS [103] are also shown, where CDMS is located at a shallow site at Stanford, but will improve its sensitivity after the planned move to a deep site in the Soudan mine.

position by WIMP collisions. The CDMS experiment [103] is currently located at a shallow site at Stanford, but will eventually move to a deep site in the Soudan mine. It uses germanium detectors and thus can discriminate against backgrounds by measuring simultaneously the bolometric and ionization signal. Unless WIMPs show up with relatively large interaction cross sections it will be inevitable to use some form of background discrimination to cover a reasonably large range of supersymmetry-motivated interaction cross sections.

There exist other ”indirect” methods to search for galactic WIMPs [26]. They would annihilate with a certain rate in the galactic halo, producing a potentially detectable background of high-energy photons or antiprotons. Moreover, they interact with the matter that makes up the Earth or Sun so that a small fraction of the WIMPs traversing these bodies will lose enough energy to be trapped and to build up at their centers. The WIMP annihilation would thus produce high-energy neutrinos from the center of the Earth and from the Sun which are detectable in neutrino telescopes. The existing limits [106] already begin to touch the parameter range relevant for supersymmetric dark matter [107]. Put another way, neutrino telescopes are already competitive with direct experiments at searching for dark matter. It depends on details of the supersymmetric models and parameters if direct search experiments or neutrino telescopes have a better chance of finding dark matter neutralinos. Roughly speaking, though, an ice Cherenkov detector like AMANDA at the south pole [108] requires a km^3 volume to be competitive with the CDMS-Soudan search goal. It is to be expected that AMANDA can actually be upgraded to this volume within the next five years or so, providing neutrino astronomy with a good chance of detecting the dark matter of our galaxy.

4.4 Axions

Axions are a particle dark-matter candidate sui generis in that they are very weakly interacting very low-mass bosons and are yet a candidate for cold dark matter, in apparent defiance of the Tremaine-Gunn argument. However, contrary to neutrinos or WIMPs, axions were never in thermal equilibrium in the

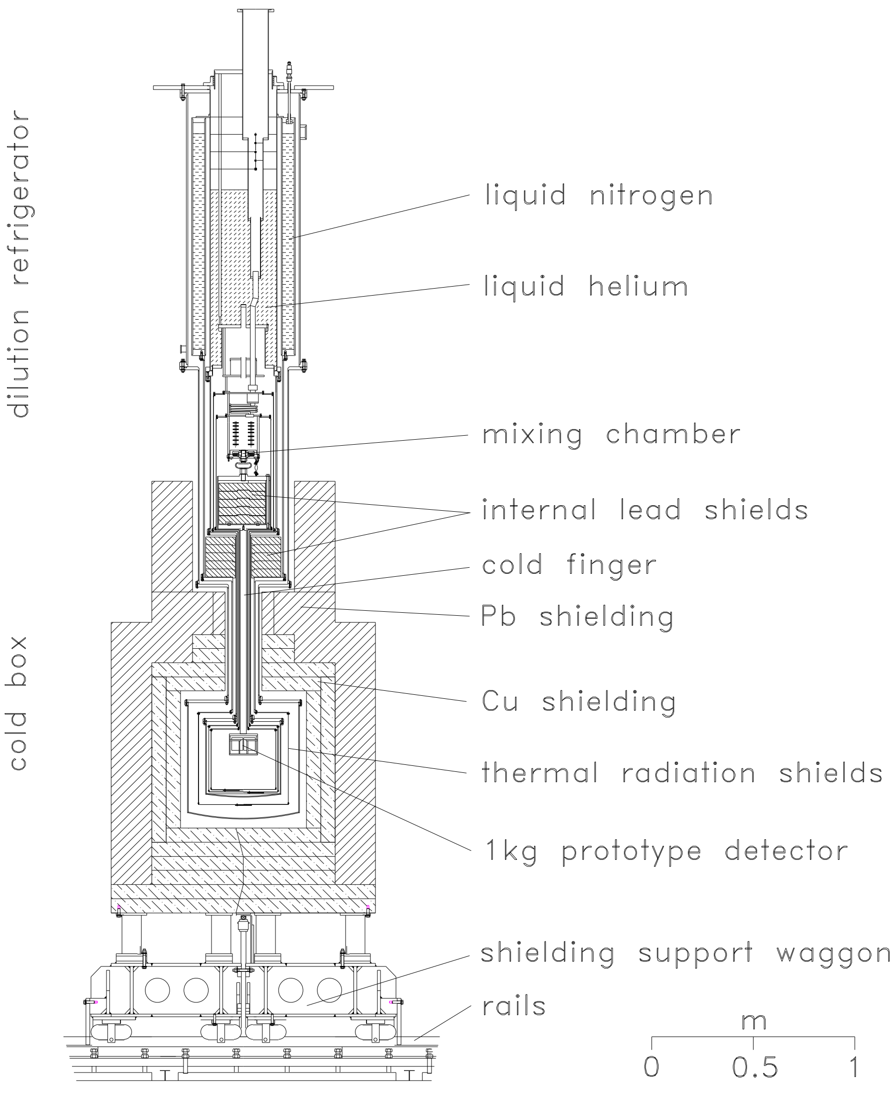

Fig. 29: Schematic view of the experimental setup of the CRESST experiment [102], located in the Gran Sasso underground laboratory near Rome (Italy), as an example for a cryogenic dark matter experiment.

early universe; they appear in the form of highly occupied and thus essentially classical oscillations of the axion field.

The existence of axions is motivated by the CP problem of QCD which consists of the observed smallness of a possible neutron electric dipole moment relative to a naive QCD expectation which would put it at roughly the same magnitude as the neutron magnetic dipole moment. Put another way, because of its nontrivial vacuum structure QCD is expected to produce CP violating effects which are measured by a parameter Θ which is an angular variable and thus can take on any value between 0 and 2π. The experimental limits on the neutron electric dipole moment (a CP-violating quantity) reveal that $\Theta \lesssim 10^{-9}$ while there is no a-priori reason why it should not be of order unity. The Peccei-Quinn solution [109] to this CP problem of the strong interaction (”strong CP problem”) is based on re-interpreting Θ as a physical field by virtue of $\Theta \to a(x)/f_a$, where $a(x)$ is the pseudoscalar axion field while f_a is an energy scale known as the Peccei-Quinn scale or axion decay constant. The main aspect of the Peccei-Quinn mechanism is that the CP-violating Lagrangian produces a potential which drives the axion-field to the CP-conserving position corresponding to $\Theta = 0$ so that CP violation is switched off by its own force. This dynamical way of restoring CP conservation can be pictured in an intruiging mechanical analogy devised by Sikivie [110].

The unavoidable quantum excitation of the new field are the axions [111]. Apart from model-dependent fine points, all of their properties are fixed by the value of f_a; for reviews see Refs. [112]. Phenomenologically, axions are closely related to neutral pions; they mix with each other with an amplitude of about f_π/f_a where $f_\pi = 93\,\mathrm{MeV}$ is the pion decay constant. Therefore, the axion mass and interactions follow roughly by scaling the corresponding π^0 properties with f_π/f_a; for example, $m_a f_a \approx m_\pi f_\pi$. The axion couplings to photons or nucleons is inversely proportional to f_a and thus arbitrarily small if f_a is sufficiently large. Analogous to π^0 axions have a two-photon coupling $\mathcal{L}_{a\gamma} = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,a$ where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic field strengths. The coupling constant is $g_{a\gamma} = -\alpha/2\pi f_a$ times a model-dependent factor of order unity. Thus far axions have not been detected in any laboratory experiment. In addition, their interaction strength can be constrained by demanding that they do not carry away more energy from the interior of stars than is compatible with astronomical observations [113]. The limits on f_a and m_a thus obtained imply that axions must be very light ($m_a \lesssim 10^{-2}\,\mathrm{eV}$) and very weakly interacting if they exist at all.

In order to understand the cosmological evolution of axions note that in concrete implementations of the Peccei-Quinn mechanism the axion field is interpreted as the phase of a new Higgs field $\Phi(x)$ which undergoes the spontaneous breakdown of a chiral $U(1)$ symmetry, the Peccei-Quinn symmetry. The potential which causes the symmetry breaking is a ”Mexican hat” with a vacuum expectation value of the ground state somewhere in the rim of the hat. The axion field is the angular degree of freedom, i.e. the axion is the Nambu-Goldstone boson of the spontaneously broken Peccei-Quinn symmetry. In the very early universe when the temperature falls below f_a the Peccei-Quinn symmetry breaks down, meaning that $\Phi(x)$ needs to find its minimum somewhere in the rim of the Mexican hat, i.e. it needs to choose one value for the axion field $a(x)$ or equivalently for the CP-violating QCD parameter Θ. Later at a temperature $T = \Lambda_{\mathrm{QCD}} \approx 200\,\mathrm{MeV}$ the QCD phase transition occurs which implies that the potential for the axion field is switched on, driving it to the CP-conserving minimum. One may equally say that at the QCD phase transition the Peccei-Quinn symmetry is explicitly broken, that the Mexican hat tilts, or that the axion mass turns on. The axion no longer is a (strictly massless) Nambu-Goldstone boson, it has become a (low-mass) pseudo Nambu-Goldstone boson.

The initial ”misalignment” Θ_i of the axion field relative to the CP-conserving minimum of the QCD-induced potential sets the axion field into motion and thus excites coherent oscillations [114]. They correspond to an axionic mass density of the present-day universe of about

$$\Omega_a h^2 \approx 1.9 \times 4^{\pm 1} (\mu\mathrm{eV}/m_a)^{1.175}\, \Theta_i^2\, F(\Theta_i). \tag{25}$$

The stated range reflects recognized uncertainties of the cosmic conditions at the QCD phase transition and uncertainties in the calculation of the temperature-dependent axion mass. The function $F(\Theta)$ with $F(0) = 1$ encapsules anharmonic corrections to the axion potential. If Θ_i is of order unity, axions with $m_a = \mathcal{O}(1\,\mu\mathrm{eV})$ provide roughly the cosmic closure density. The equivalent Peccei-Quinn scale $f_a = \mathcal{O}(10^{12}\,\mathrm{GeV})$ is far below the GUT scale so that one may speculate that cosmic inflation, if it occurred at all, did not occur after the PQ phase transition.

If it did not occur at all, or if it did occur before the PQ transition with $T_{\mathrm{reheat}} > f_a$, the axion field will start with a different Θ_i in each region which is causally connected at $T \approx f_a$. Then one has to average over all regions to obtain the present-day axion density. More importantly, because axions are the Nambu-Goldstone mode of a complex Higgs field after the spontaneous breakdown of a global U(1) symmetry, cosmic axion strings will form by the Kibble mechanism [115]. The motion of these global strings is damped primarily by the emission of axions rather than gravitational waves. At the QCD phase transition the U(1) symmetry is explicitly broken (axions acquire a mass) causing domain walls bounded by strings to form which get sliced up by the interaction with strings. The whole string and domain-wall system will quickly decay into axions. This complicated sequence of events leads to the production of the dominant contribution of cosmic axions where most of them are produced near the QCD transition. After they acquire a mass they are nonrelativistic or mildly relativistic so that they are quickly redshifted to nonrelativistic velocities. The proper treatment of axion radiation by global strings is difficult and has been partly controversial. However, taking account of all recognized uncertainties one arrives at a plausible range for the mass of dark-matter axions between a few $\mu\mathrm{eV}$ and a few meV.

The axions produced by strings or the misalignment mechanism were never in thermal equilibrium; the field modes are highly occupied, forming something like a Bose-Einstein condensate. Axions are nonrelativistic almost from the start and thus form cold dark matter, in spite of their small mass. If the axion interaction were sufficiently strong ($f_a \lesssim 10^8\,\mathrm{GeV}$) they would have come into thermal equilibrium before the QCD phase transition, leading to an axion background in analogy to the one expected for neutrinos [116]. However, this parameter range is excluded by the astrophysical arguments which imply that axions interact so weakly that they have never come into thermal equilibrium in the early universe. They cannot provide a hot dark matter component.

If axions are the galactic dark matter one can search for them in the laboratory. The detection principle is analogous to the Primakoff effect for neutral pions which can convert into photons in the presence of an external electromagnetic field due to their two-photon vertex (Fig. 30). Dark matter axions would have a mass in the $\mu\mathrm{eV}$ to meV range. Because they are bound to the galaxy their velocity dispersion is of order the galactic virial velocity of around $10^{-3}c$ so that their kinetic energy is exceedingly small relative to their rest mass. Noting that a frequency of $1\,\mathrm{GHz}$ corresponds to $4\,\mu\mathrm{eV}$ the Primakoff conversion produces microwaves. Because the galactic axions are nonrelativistic while the resulting photons are massless the conversion involves a huge momentum mismatch which can be overcome by looking for the appearance of excitations of a microwave cavity rather than for free photons.

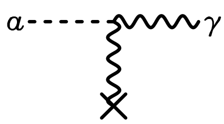

Fig. 30: Primakoff conversion of axions into photons in the presence of an external electromagnetic field.

An axion search experiment thus consists of a high-Q microwave resonator placed in a strong external magnetic field ("axion haloscope" [117]). The microwave power output of such a cavity detector on resonance is [117, 118]

$$P \approx 0.4 \times 10^{-22}\,\mathrm{Watts} \left(\frac{V}{0.2\,\mathrm{m}^3}\right) \left(\frac{B}{7.7\,\mathrm{Tesla}}\right)^2 \left(\frac{C}{0.65}\right) \left(\frac{Q}{10^5}\right) \left(\frac{\rho_a}{300\,\mathrm{MeV\,cm}^{-3}}\right) \left(\frac{m_a}{1\,\mu\mathrm{eV}}\right), \tag{26}$$

where V is the cavity volume, B the applied magnetic field strength, C a mode-dependent form factor which is largest for the fundamental T_{010} mode, Q the loaded quality factor, and ρ_a the local galactic axion density. This is indeed a weak microwave signal! If m_a were known it would be easy to detect galactic axions with this method. One may verify or reject a tentative signal by varying, for example, the applied magnetic field strength. Therefore, contrary to the WIMP experiments it would be hard to mistake a background signal for a dark-matter signature. The problem is, of course, that m_a is not known so that one needs a tunable cavity, stepping its resonance through as large a frequency range as possible and to look for the appearance of microwave power beyond thermal and amplifier noise.

Two pilot experiments of this sort [119, 120] have excluded the range of axion masses and coupling strengths indicated in Fig. 31. Evidently, for a standard local halo density of about $300\,\mathrm{MeV\,cm^{-3}}$ they were not sensitive enough to reach realistic axion models. Two current experiments with much larger cavity volumes, however, have the requisite sensitivity; their search goals are depicted in Fig. 31. In its current setup, the Livermore experiment [121] uses conventional microwave amplifiers which limit the useful cavity temperature to about $1.4\,\mathrm{K}$. The Kyoto experiment CARRACK [122], on the other hand uses a completely novel detection technique based on the excitation of a beam of Rydberg atoms which passes through the cavity. This is essentially a counting method for microwaves which does not require a (noisy) amplifier so that one can go to much lower physical cavity temperatures. This enhances the sensitivity and also allows one to use smaller cavity volumes and thus to search for larger axion masses.

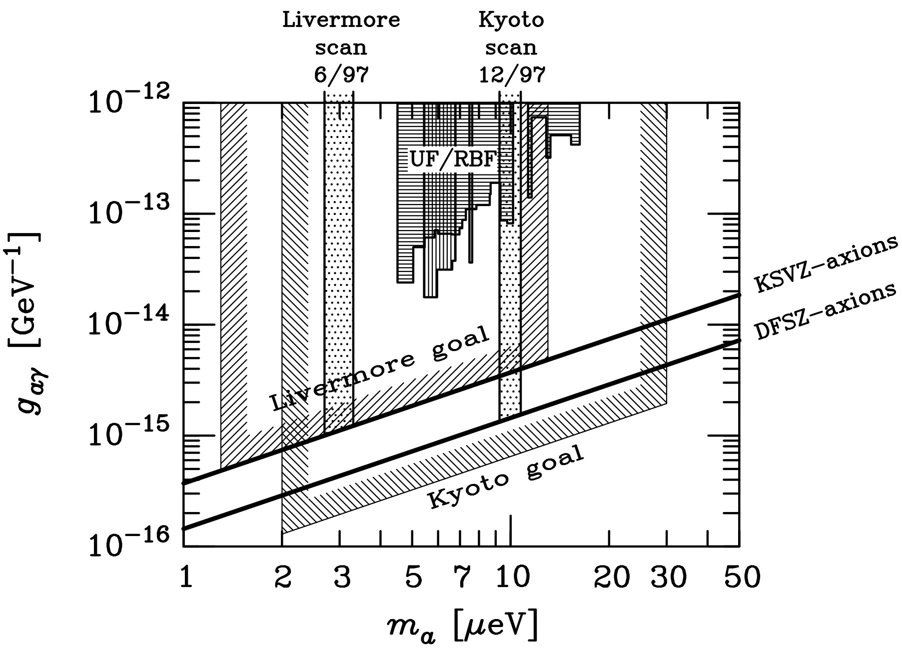

Fig. 31: Current limits on galactic dark matter axions from the University of Florida (UF) [119] and the Rochester-Brookhaven-Fermilab (RBF) [120] search experiments and search goals of the current Livermore [121] and Kyoto [122] experiments. It was assumed that the local galactic axion density is $300\,\mathrm{MeV\,cm^{-3}}$.

In summary, the second generation axion experiments have reached a sensitivity where they may well turn up axion dark matter during their expected running time of a few years. If they fail to find axions it would be extremely important to extend the experimental search into a regime of larger masses toward the meV scale.

4.5 Primordial Black Holes

Stellar-remnant black holes collapse from baryonic material and are thus probably excluded as dark-matter candidates [68]. Primordial black holes which form before big-bang nucleosynthesis, on the other hand, are perfect cold dark matter candidates; in a sense they are just particularly fat WIMPs. The microlensing observations of apparent MACHOs as a significant dark-matter component of the galactic halo has revived the interest in these objects. The main objection against them is the lack of a plausible mechanism for making them in the early universe, even though there have been some intruiging recent suggestions [123]. In any event, as long as particle dark matter remains undiscovered the option of primordial black holes as a CDM candidate should not be forgotten.

4.6 Modified Gravity

The hypothesis of particle dark matter requires nontrivial and perhaps bewildering extensions of the particle-physics standard model. As long as the nature of dark matter has not been positively identified it may seem no more radical to try to modify general relativity such that there is no need for dark matter. It has sometimes been argued that the hypothesis of dark matter is just a parametrization of our ignorance of the physical laws which apply on large astrophysical scales where no independent test of the validity of general relativity exists that would not involve the hypothesis of dark matter.

In one phenomenological approach known as MOND for Modified Newtonian Dynamics [124] gravitational accelerations a below a certain limit a_0 are given by $a^2/a_0 = G_{\rm N}M/r^2$, where $G_{\rm N}$ is Newton's constant. With $a_0 \approx 10^{-8}\,{\rm cm\,s^{-2}}$ this approach is surprisingly successful at explaining a broad range of dark-matter phenomena related to dwarf galaxies, spiral galaxies, and galaxy clusters [124, 125]. Unfortunately, MOND lacks a relativistic formulation so that it cannot be applied on cosmological scales.

One covariant alternative to general relativity is a conformally invariant fourth-order theory [126]. In the nonrelativistic regime it leads to a linear potential in addition to the Newtonian r^{-1} term. It explains at least some of the galactic and cluster dark-matter problems.

Before modifications of general relativity can be taken seriously they must pass relativistic tests. An important case are galaxy clusters where large amounts of dark matter are indicated by nonrelativistic methods (virial theorem) as well as by relativistic indicators (gravitational lensing, notably giant arcs). Because virial and lensing masses seem to agree well in several cases, scalar-tensor extensions of general relativity are in big trouble, if not ruled out entirely [127]. One way out could be a certain preferred-frame theory which can reproduce the MOND phenomenology as well as the lensing effects [128].

Apparently, no serious attempt has been made to discuss truly cosmological phenomena such as structure formation and cosmic microwave background distortions in the framework of alternative theories of gravity. At the present time it is not known if a covariant theory of gravity exists that can explain the dark-matter problems on all scales. However, as long as the nature of dark matter has not been identified one should keep an open mind to such possibilities!

5 CONCLUSION

There is now little doubt that the dynamics of the universe on galactic scales and above is dominated by dark matter which almost certainly is not in the form of objects which are familiar to us. Much of the evidence points in the direction of a cosmic background of new weakly interacting particles, with neutralinos, axions, and neutrinos the favored options because they are well motivated by particle-physics theory for reasons other than pleasing the astronomers. At the present time the existence of dark matter is perhaps the strongest empirical evidence for particle physics beyond the standard model.

Over the past decade one has become used to the idea that most of the stuff in the universe consists of nonbaryonic matter. Yet this remains a radical conjecture which has often been likened to the Copernican revolution when Earth and with it Man was moved from the center of creation to some unspectacular average position. Probably the next big step in the Second Copernican Revolution will be the final deciphering of the ”Cosmic Rosetta Stone” in the form of precision measurements of the angular temperature fluctuations of the cosmic microwave background which will confirm or refute the apparent discrepancy between the baryon content of the universe and its dynamical mass density. Even then, however, this second revolution will not be complete without a direct and positive identification of the dark matter particles or objects. Therefore, the search experiments for galactic dark matter as well as the laboratory searches for supersymmetric particles and neutrino masses are among the most important scientific enterprises in our attempt to understand the universe.

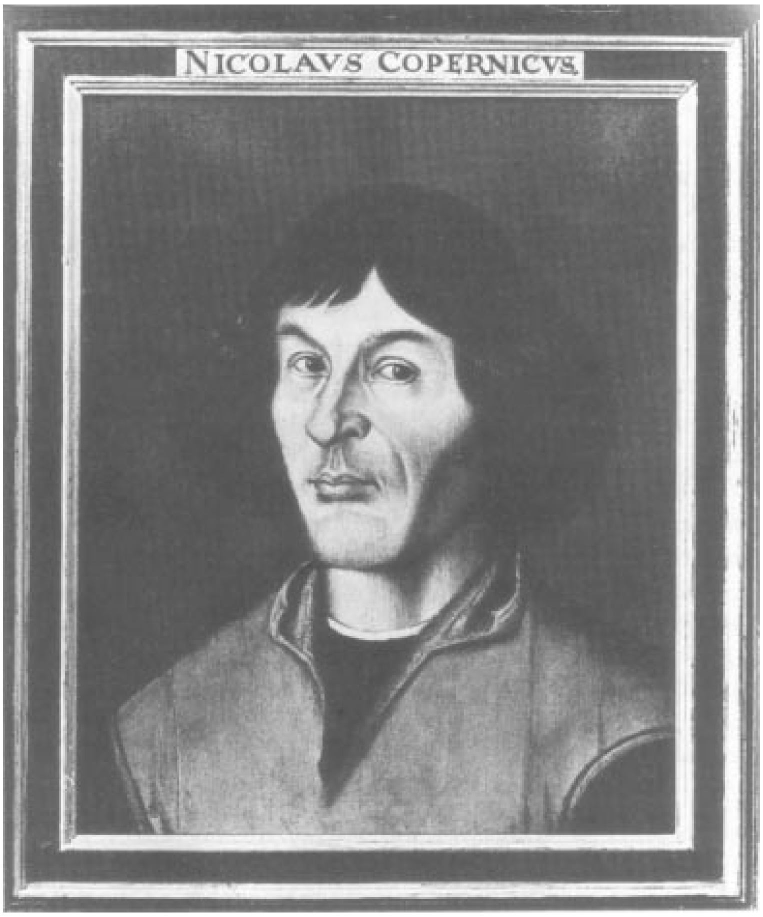

Fig. 32: Nicolaus Copernicus (1473−1543).

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